Plant selection for green roofs in the UK

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Abstract

The use of green roofs is increasing in many countries because of their benefits to the urban environment. However, only a few plant selection studies for green roofs have been carried out and little information on plant performance on roof environments is available in the UK climate. As a result, only a limited range of plants such as *Sedum* spp. are commonly used for green roofs, especially for shallow substrate green roofs. Therefore, this thesis investigates plant selection for extensive green roofs in the UK. The work in this thesis focused on the following objectives. (1) To identify groups of plants that have potential for use on green roofs, with regard to tolerance of rooftop conditions, (2) To investigate establishment methods for diverse, attractive, flowering green roof vegetation, with attention to seedling techniques, (3) To test survival and performance of a selected range of species and cultivars from the previously identified groups (annuals and geophytes) at different substrate depths, irrigation regimes and covering plants treatments, (4) To compare green roof performance (water management and drought tolerance) between different vegetation types and drought tolerance with different percentages of organic matter in the growing substrate, (5) To investigate the performance of plants as well as their aesthetic appeal, seasonal interest over time and what is required for maintenance (weed invasion and self-seeding).

The direct sowing of perennial and grass mixtures, the use of annual plant seed mixtures and the use of geophytes could be useful techniques for the quick establishment, long flowering, their beautiful colour of flowers, cost effectiveness and providing food resources for biodiversity in an extensive green roof. Germination testing revealed that many perennial and grasses which have potential for use in extensive green roofs did not require chilling for germination and had high germination rates in spring. The results suggested that spring might be the best season for direct sowing on the roofs for quick establishment. In annual plant meadows, it was shown that a low sowing density could be better than high density to reduce competition, resulting in good individual plant growth when there was sufficient watering. However, a high sowing density was recommended for the dry conditions. For geophytes, growth, survival rate, regeneration and flowering were more successful in a deeper substrate rather than a shallow substrate. The vegetation cover by *Sedum* seemed to work as a protection layer and the overall emergence was encouraged with *Sedum*, especially in the shallow substrate.

In the study of amount of water runoff from different vegetation types, it was shown that grass species may be the most effective for reduction of water runoff followed by forbs and sedums. The size and structure of plants significantly influenced the amount of water runoff, however, species richness did not affect the amount of water runoff significantly. In the study of the drought tolerance of different vegetation types, the forbs and grasses groups used in this study reached permanent wilting point after two to three weeks of no watering and they were required to be watered once a week to maintain their visually attractive forms. *Sedum* spp. were able to survive well and maintain good visual quality even after three weeks of no watering. There was a tendency that overall survival increased as species richness increased. The diversity in vegetation reduced the vigor of potential dominant species. In the investigation of the relationship between percentage of organic matter of substrate and plant growth, it was concluded that about 10% (about 14% in total) of organic matter was the best because the plants showed stable growth regardless of the watering regime. In wet conditions, increased organic matter resulted in increased growth, whereas in the dry conditions, increased organic matter did not result in increased growth.

In the investigation of plant growth and performance on an existing semi-extensive green roof it was shown that is it is possible to create low-input green roofs which have long flowering and seasonal interest with a little maintenance and supplemental irrigation if appropriate plants were chosen. Plant species diversity might affect overall flowering succession and dynamic change and planting density might affect interaction between plants. In areas of high plant species diversity, there were more possibilities to have a longer flowering term, more seasonal interest and dynamic change than low plant species diversity. In areas of low planting density, individual plants generally produced the better growth than those in high planting density. Moreover, plant growth had more interaction between species in the higher planting density. The tendency was observed that the plants had better growth in the NE and the SE. Also, longer flower duration was shown in the NW whereas many species started flower from the SE. The combination of low plant species diversity and high planting density appeared to reduce weeds effectively. Using a gravel much in the shallow substrate could reduce the number of weeds significantly.

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Contents

All photographs in this thesis were taken by the author unless noticed.

Chapter 1 Introduction

1. Introduction

Big cities tend to have many environmental problems because of a reduction of green space, a high concentration of people, buildings and transportation, and huge energy use. Many of these problems are direct results of a lack of green space and nature in cities. A green roof (an area of planting with a substrate isolated from the natural ground by a man-made structure of at least one story (Brownlie, 1990), is one of the important strategies to help address some of the key urban environmental issues. Green roofs can:

- Reduce water runoff and improve the quality of water
- Create the habitat for wildlife
- Moderate heat island effect
- Improve the insulation and energy efficiency
- Improve the air quality
- Create aesthetic and amenity value
- The place for urban food production
- Increased the roof life

(English Nature, 2003, and Dunnett and Kingsbury, 2004 a).

Because of these benefits, the use of green roofs is increasing in big cities. In Germany, Switzerland, Japan and North America, city governments support green roofs financially, and instalment is required to get planning permission for buildings in some areas. However, although it seems that the concept of green roofs and their benefits are easy to understand, it had been difficult to find the detail technologies and plant species which can be used for green roofs. This situation has changed in these 5 years. Through the proceedings of green roof conferences (e.g. Greening Rooftops for Sustainable Communities) and several green roof books (e.g. 'Planting green roofs and living walls' by Dunnett and Kingsbury (2004a), 'Green roofs, Ecological Design and Construction' by Earth Pledge (2005), 'Green roof plants' by Snodgrass and Snodgrass (2006)), it is possible to get much more information which is necessary for the green roof instalment.

However, there is a tendency that only a limited range of plants are used for green roofs, especially for shallow substrate green roofs. Indeed, *Sedum* spp., the species which have very high water use efficiencies and perform well where many of other species are not able to survive, are commonly used for green roofs internationally, and some people even believe that a green roof is a synonym of sedum roof. One of the reasons for this might be a lack of investigation into the range of possible plants, and this has resulted in a belief that only a restricted range of specialized species will survive on shallow substrate of green roofs which are subject to the most extreme environmental conditions (Dunnett and Kingsbury, 2004a). Especially, where the function of a green roof is to go beyond the efficient fulfilment of engineer requirements (water management and thermal regulation, for example) to embrace aesthetics and biodiversity, it is worth considering carefully the options that are available (Dunnett et al., 2005). Generally, the green roof environment is severe for plant growth. However, it is important to understand which species are likely to perform well in the limited conditions of green roofs (depth of substrate, microclimate, maintenance, additional irrigation, cost) and which species are appropriate to achieve their goal for green roof instalment and aesthetics rather than simply choosing from a very limited plant list for green roofs.

Therefore, this thesis aims to investigate the potential of selected herbaceous plant groups for use on green roofs in the UK. This introductory chapter summarizes the background of green roofs, especially related to vegetation and considers three main questions:

1) What is a green roof? What kind of green roofs exist and what are their characteristics?
2) How the use of vegetations for green roofs has been developed in the different countries?
3) What are the benefits to use wide range of plants for green roofs?

2. Definition of green roofs

Typical green roofs consist of a waterproof membrane, root protection barrier, drainage layer, growing substrate and vegetation (Fig.1.1). Green roofs can be mainly divided into two types: intensive green roofs and extensive green roofs. Their characteristics are explained as follows.

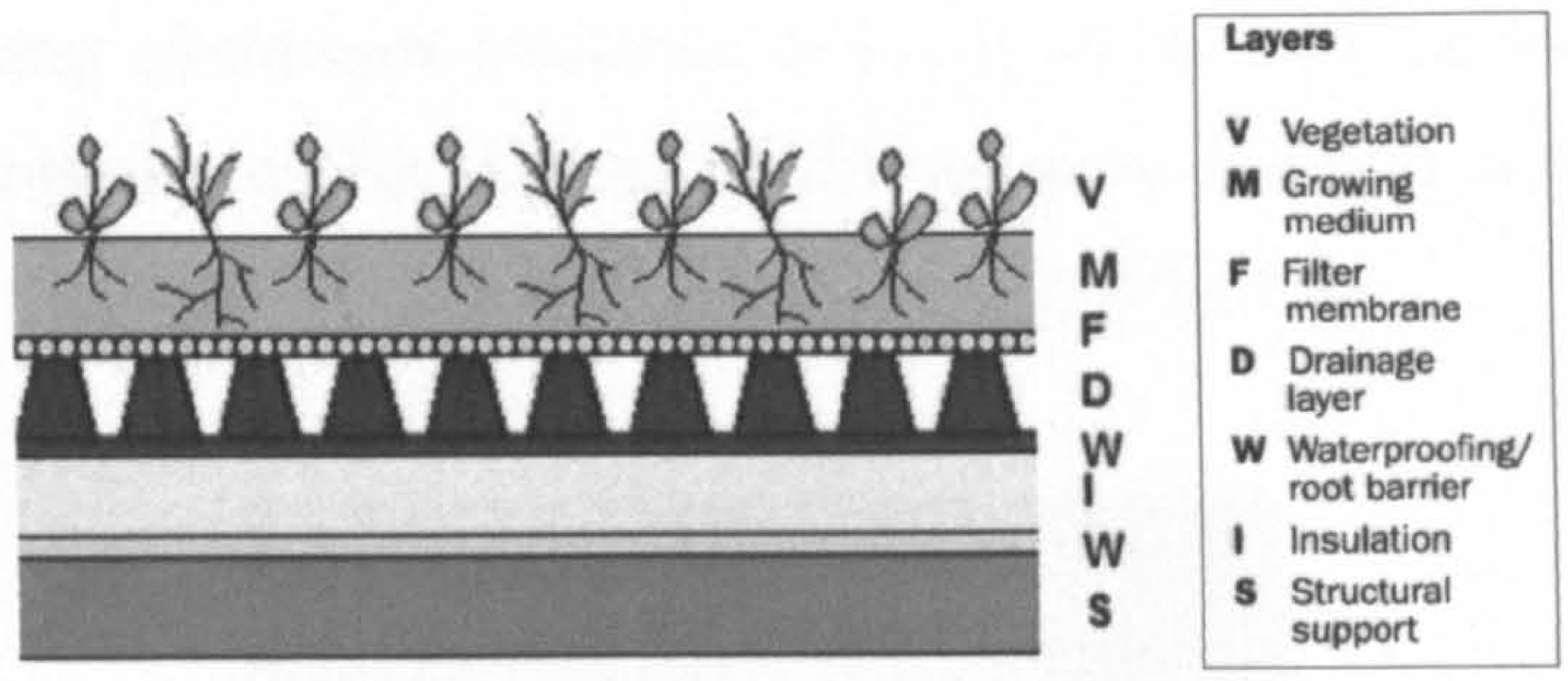


Fig. 1.1 Typical component of green roof (Source: Oberndorfer,et al., 2007)

2.1 Intensive green roofs

Intensive green roofs are characterized by a thick depth of substrate (more than 20 cm), usually having irrigation systems, involving high maintenance and high cost. A wide variety of plant species can be used. It is possible to create gardens which are similar to those on the ground. This type of green roof has been used as the leisure place for a long time in many countries. Common places for use of intensive green roofs are residences, hotels, restaurants, office buildings, shopping centres and hospitals. Fine examples of intensive green roofs are introduced in 'Roof Gardens, History, Design, Construction' by Osmundson (1999). However, intensive green roofs can be installed for only a limited range of buildings since they should be structurally strong enough to support the heavy weight of substrate and they require regular maintenance and high cost.

There are many types of intensive green roofs because many kinds of vegetations can be used. However, they might be mainly divided into five: (1) Intensive green roofs using containers (2) Simple intensive green roofs (highest planting may be shrubs) (3) Complex intensive green roofs (including trees and sometimes water features) (4) Ecological intensive green roofs (Intensive green roofs using ecological methodologies) and (5) Green roofs for agriculture (food productions). Traditionally, intensive green roofs using containers, simple intensive green roofs and complex intensive green roofs are used to create aesthetic for amenity places. Contemporary intensive green roofs tend to require more than aesthetics; they consider more ecology and environmental benefits. Moreover, sometimes they are used as functional places such as food productions.

2.1.1 Intensive green roofs using containers

This type of intensive green roof is commonly used at just above ground level or on top of structures such as underground parking garages (Osmundson 1999). In these open spaces, generally, intensive green roofs are used with hard landscape and only a part of roof is planted using containers because of accessibility and the reduction of cost for instalment and maintenance. For example, 220 trees of *Zelkova serrata* were planted using containers in the open square in Saitama Japan (Fig.1.2).

Fig.1.2 Keyaki square in Saitama, Japan

Traditionally, building edge planting is also often observed. This is analogous to an enormous window box: strip planting on the edge of a building rather than on the roof itself. This creates a far softer appearance than that conveyed by the sterile concrete structures found in many cities (Osmundson, 1999). In balconies at Broadgate in London, plants create appealing points of interest (Fig.1.3).

Fig. 1.3 Building edge planting at Broadgate in London, UK

2.1.2 Simple intensive green roofs

Intensive green roofs using simple vegetation do not demand very high load-bearing capacity and they are less expensive than intensive green roofs with a high variety of planting including trees. However, they still require regular maintenance, including irrigation, feeding and cutting (English Nature, 2003). The substrate depth is up to 50 cm, and the tallest plants used may be shrubs. In many cases, this type of intensive green roof is used to enjoy the view from the roof. For example, in Wills Faber & Dumas, an office building in Ipswich, UK, the simple intensive green roof was installed with the concept of classic simplicity with railings, a footpath and a hedge surrounding a lawn (Fig. 1.4). The hedge is clipped to the height of the railings screening the foreground of the city panorama (Jack, 1992).

Fig.1.4 Wills Faber & Dumas in Ipswich, UK

2.1.3 Complex intensive green roofs

Using a wide range of plant species including trees, sometimes water features, it is possible to create a separate world on the roof. The classic example of intensive green roof Derry and Toms in London, opened in 1938, has high enclosing walls, substantial masonry pergolas with luxuriant vines, mature trees and streams, which gives no clue to its being on the seventh floor (Jack, 1992). This type of green roof has the highest demands on the building structure and is the most expensive to build and maintain, although it will usually form a very small part of the overall cost of the development that it is associated with (English Nature, 2003). According to Scrivens (2004), no group of plants can be said to be unsuitable for use in an intensive green roof. Large forest trees may be impracticable because of problems with anchorage, but other than that almost any plant used in general landscape is capable of prospering, although it is important to consider how they will tolerate the environment of exists on the roof, such as exposure, drought, stability and planting density.

2.1.4 Ecological intensive green roof

Although intensive green roofs require a certain input such as materials, watering, fertilizer and maintenance, it is becoming important to use more ecological methodologies. This is mainly because nowadays green roofs tend to be installed to achieve environmental benefits and it makes sense to be aware of ecology. The ecological theme can be extended still further through water recycling, water storage, and harnessing the solar and wind energy that is available in abundance at roof level (Dunnett and Kingsbury, 2004 a).

In intensive green roof 'Kawasaki Urban bio' in Japan, some ecological methodologies were used. Similarly to other ecological green roofs, there are wetlands including *Rumex japonicus, Cyperus microiria* and *Paspalum dilatatum* to attract birds and invertebrates. Recycled water was used and wind hybrid power system provides the energy for the pump. The green roof was designed to recreate similar gardens which used to be seen in this area. Therefore, the natural soil and trees which were on the site before construction were preserved and reused for the green roofs. The green roof consists of two areas, the lower roof (volcanogenous soil + perlite, 40cm depth of soil, 320 m^2) including ecological patch (Top soil from the site + volcanogenous soil, 40cm depth of soil, 8 m^2), the higher roof (commercial green roof substrate 20-40cm depth, 150 m^2). (Figs.1.5-1.6). (Osawa et al., 2002). In addition, trees such as *Ficus carica* which grew on the site were transplanted or cut down and used as benches on the roof.

Figs.1.5-1.6 Kawasaki Urban bio green roof in Kanagawa, Japan

2.1.5 Green roofs for agriculture (food productions)

Roof surfaces offer one opportunity for growing healthy food, particularly in high-density urban areas or where garden space may be small or restricted (Dunnett and Kingsbury, 2004a). On the Reading International Solidarity Centre (RISC) edible roof garden, more than 120 species of plants from around the world were planted (Fig.1.7). These plants were carefully chosen for productive uses, whether medical, fruit-producing or simply weed-smothering. The planting is based on the Forest Garden concept by Robert Hart, echoing the layered ecosystem naturally found in a forest: small bulbs, herbaceous perennials and ground cover plants grow below a shrubby layer, above which is a canopy of ornamental and fruiting trees, all linked together with vines and climbers. An automatic irrigation system is run by the wind power and the solar panel, and the collected rainwater is used. The roof has 30 cm substrate depth and maintenance is 3-4 times in a month, however, plant growth is excellent, including fruits trees. Fresh salads and herbs are produced for use in the RISC cafe in downstairs and any kitchen waste from the cafe is composted from the garden (Jones, 2005).

Fig.1.7 RISC edible roof garden in Reading, UK

2.2 Extensive green roofs

Extensive green roofs are characterized by low maintenance, little or no irrigation systems, thin substrate depths (2cm-20cm), and having a light weight (Johnston and Newton, 1993). Nowadays, extensive green roofs become common because they are easy to be introduced for existing buildings without structural modification and they require low maintenance and low cost. In addition, they are appropriate for large areas. However, one of the main limitations of extensive green roofs is their limited plant selection. Less species of plants can be used in extensive green roofs because of their thin soil, irregular rain input, exposure of high radiation and strong wind. Extensive green roofs can be divided into six main types: (1) Monoculture green roofs (2) Spontaneous green roofs (3) Brown roofs (4) Dry meadow green roofs (5) Semi-extensive green roofs (6) Wetland green roofs. These types of green roofs and their characteristics are explained as follows.

2.2.1 Monoculture green roofs

Succulents such as Sedums and turf are often used for monoculture green roofs. Sedums are the most commonly used genus for extensive green roofs because they have very high water use efficiencies and perform well where many of other species are not able to survive. They require only shallow substrate (about 5cm in the UK) and are easy to establish. Monocultures can give a simple, clean appearance and neat and tidy impression as it is shown in Fig.1.8. However, monoculture green roofs are often visually rather uninteresting and susceptible to total die-back if drought or disease severely affect the plant (Dunnett and Kingsbury, 2004a). Even though the green roof environment allows growing only limited plant species, it is recommended to use several species to increase visual interest, long flowering and dynamic aspects. For example, the addition of a single upright or vertical species, such as short *Festuca* species, *Allium schoenoprasum* among Sedums can create visual diversity (Dunnett, 2004c) .

Fig.1.8 Sedum green roof in Chelsea flower show (2003) in London, UK

2.2.2 Spontaneous green roofs

In spontaneous green roofs, the vegetation is left as naturally colonized, although sometimes a seed mixture is used initially. They also help sites to blend with the surrounding landscape and provide islands and corridors of nature conservation value (Bayfield, 2004). The self build green roofs, Romily roofs in Hereford UK, used the vernacular soil and plants initially and were left as colonized (Fig. 1.9). According to the observations by the author, the roofs are dominated by grasses such as *Anthoxanthum odorathum* and *Festuca rubra*. As well as grasses, some ornamental plants such as *Muscari armeniacum, Primula veris, Euphorbia cyparissias* also can be found on the roof. However, because vegetation developments rely on only colonized plants and microclimate, there is the possibility that their appearance become not visually attractive and they may have limited species diversity.

Fig.1.9 Romily roof in Hereford UK (Photograph: Noel Kingsbury)

2.2.3 Brown roofs (Living roofs)

Brown roofs (Living roofs) are one type of spontaneous green roofs and are specifically designed to create habitats for biodiversity. They are characterized by use of native species, locally characteristic plant communities, local provenance material and local ecotypes and local soils and substrate materials (Dunnett, 2006a). The use of the term 'brown roof' was intended to indicate that these roofs do not remain green throughout the year. Usually, the depth of substrate is not uniform so that they can provide a variety of habitat condition for different vegetation structures and possibilities for organisms to retreat in dry periods. Some areas on the green roof are only sparsely vegetated, or not vegetated at all, to accommodate for birds and other organisms with locomotion adapted to open spaces (Brenneisen, 2003). Dead branches tend to be used for perches that are the preferred terrain of insect-hunting birds (Earth Pledge, 2005). These characteristics are observed in the green roof of Canton's Hospital, Basel in Switzerland (Fig.1.10-1.11). While technically a green roof, its surface is actually more brown than green, to mimic the appearance of the surrounding barren landscape in an artificial habitat for the birds (Frith and Gedge, 2005). Brown roofs are well developed and studied in Basel, Switzerland and in London, UK.

Figs.1.10-1.11 Canton's Hospital in Basel, Switzerland

2.2.4 Dry meadow green roofs

Plant community-based plantings are suitable for extensive green roofs because they are self-sustaining, requiring low maintenance and they can compensate for stressful periods of the year for the different species and they overcome and withstand the environmental hazards (Dunnett and Kingsbury, 2004a). Although they share some characteristics with roofs created through the use of spontaneous vegetation, dry meadow green roofs are created with pre-determined species mixes so that there is more control over species composition and the aesthetic appearance of the roofs. In one example, a Chicken farm on the Asphof, Rothenfluh green roof was installed using 15cm of China reed, a very light and water storing ground layer, topped by 5cm topsoil

(Brenneisen, 2004) (Fig.1.12). *Phacelia* were sown at first because it is a fast-growing species and improve the soil and prevent erosion. Mown grass from a dry meadow is spread on top of this to promote the establishment (Brenneisen, 2005c). There are many types of dry meadows in nature, which can be used for green roofs. Some examples include North American prairies, Central European Steppe and limestone vegetation. The potential natural habitats for dry meadow green roofs will be introduced in Chapter 2.

Fig. 1.12 Asphof green roof in Switzerland

2.2.5 Semi-extensive green roofs

A semi-extensive green roof is a type of green roof between intensive and extensive. They have a slightly greater depth of growing media up to 20cm and have low-input philosophy behind their creation. This allows for accessible and visually pleasing green roofs without the need for significant additional structural support and also allows for a more interesting range of drought tolerant plants to be grown (Dunnett and Nolan, 2004). One of the best examples of a semi-extensive green roof is Moorgate Crofts Business Centre in Rotherham, UK (Fig.1.13). In this green roof, as well as low growing species, medium height clump forming species such as *Calamintha nepeta*, taller emergent species such as *Kniphofia* 'Border Ballet' are used (Dunnett and Nolan, 2004). The detail of the green roof in Moorgate Crofts Business Centre will be introduced in Chapter 5. However, semi-extensive green roofs are more expensive than above extensive green roofs. This is because they use a large number of plant species including more expensive plants, pot plants or plug plants might be used and it is necessary to consider about irrigation and more regular maintenance. This type of planting is appropriate for accessible or highly visible places. Semi-extensive green roofs could be seen as a viable and sustainable alternative to intensive green roofs, to create more ecological and sustainable green roofs.

Fig.1.13 Moorgate Crofts Business Centre in Rotherham

2.2.6 Wetland green roof

While green roofs are regarded as primarily dry habitats, if drainage is impeded, it is also possible to have wetland vegetation on a roof. There are not many examples right now, but wetland green roofs, which have thin soil and require low maintenance, have great potential. A great variety of plants and animals from an aquatic or wetland environment can increase the amenity and wild life interest on the roof (Johnston and Newton, 1993). The rain water might be collected in the substrate or pond, which is useful to reduce water runoff. In addition, the rain water quality might be improved through filtration through the substrate. For example, the Possmann Company, a German apple cider maker uses wetland green roof to keep its cider cool during fermentation. Rainwater collected in the wetland circulates into the factory to cool the tanks and then back to the roof. The plants thrive in the warmed water, and the shady root zone cools the water again before it flows back to the factory (Earth Pledge, 2005). However, such roofs require additional weight loading because of the permanently saturated substrate and higher cost for instalment and equipments and regular maintenance of this equipment are required for wetland green roofs although the plants require low maintenance – this is perhaps why they have not achieved wider use.

Fig.1.14-15 Possmann Cider Company in Germany

(Source: Earth Pledge,2005)

2.3 Summary

When the vegetations are chosen for green roofs, it is necessary to consider whether they fulfil the requirement of green roofs such as substrate depth (generally related with weight of load), maintenance, cost for instalment and necessity of irrigation. The deeper the substrate, the more planting options are available, however, the cost of instalment, the necessity of maintenance and irrigation systems become higher. The relationship between vegetation types and these requirements is summarized in Table 1.1.

Table 1.1 Summary of different types of green roofs (Classified by the author)

Vegetation type	Maintenance	Cost for instalment	Necessity of irrigation	Choice of plant species	Appropriate substrate depth			
					2-5cm	5-10cm	10-20cm	More than 20cm
Extensive Monoculture	Low	Low	Low	Limited				
Extensive Spontaneous	Low	Low	Low	Limited				
Extensive Dry meadow	Medium	Low	Medium	Medium				
Semi-extensive Mixed planting	Medium	Medium-High	Medium-High	Medium				
Semi-extensive Wetland	Medium-High	Medium-High	-	Medium				
Intensive green roofs Mixed planting	High	High	High	High				

3. Vegetation development of extensive green roofs in different countries

Although green roofs have developed internationally recently, intensive green roofs have a long history. One of the oldest recorded green roofs were the hanging gardens of Babylon, built around 500 B.C. in southern Iraq. The building structure was strong enough to support the various plants including tall trees, they were irrigated and regularly maintained. This kind of intensive green roof has been installed internationally for a long time. It was from the middle of the 1800s that green roofs started to be applied more frequently on buildings. This development was brought about by the invention of reinforced concrete and new materials such as water proofing (Martínez, 2005). However, intensive green roofs have been limited to luxurious buildings because of high cost of instalment and maintenance and generally, planting materials have not been taken seriously.

The vegetation for intensive green roofs is various, however, it seems that the certain vegetations are commonly installed for extensive green roofs in individual countries. This is because the motivating factors for green-roof implementation in different regions can be quite different, according to climatic, cultural, and political factors, and as a result, the level and type of incentives to promote their use can also vary (Dunnett and Kingsbury, 2004a). There has been little review to compare and see the difference of vegetation use for green roofs in different countries. The exceptions are the two books by Dunnett and Kingsbury (2004a) and Earth Pledge (2005). However, the former is more focused on culture background and policy and the latter mainly include case studies and very few studies can be found for vegetation development of green roofs.

The aim of this section is to study the plant selection and their development for extensive green roofs in different in six major countries (Germany, North America, Switzerland, UK, Sweden, Japan), through literature review and site visits. This study is focused on vegetation use in different climates and countries because a review of vegetation development of green roofs helps to understand what kinds of factors might be important for plant selection. It also leads us to understand what kind of plant selection research will be important in the future. The following questions were considered for each country.

1) What kind of extensive green roofs was traditionally used?
2) How did extensive green roofs start to develop?
3) What kind of vegetations has been commonly used for green roofs recently?
4) Were their green roof vegetations influenced by the other countries? If so, how were they applied to adapt their country?
5) What factors did influence the development of extensive green roofs?

3.1 Germany

Germany has a long history of contemporary green roof development and it is regarded as the centre of green-roof activity throughout the world. Green roofs started to be installed in Germany from the 1970s, much earlier than the other countries because of the country's national environmental consciousness. Historically, extensive green roofs were the result of unintentional innovation in the late 1880s. These green roofs were originally covered with the fire and weather proofing layer of sand and gravel and eventually covered with vegetations. The green roof of the water pumping station in Berlin Grunewald is an early example of vegetation used for insulation (Fig. 1.16). This nineteenth-century roof was greened to keep the drinking water cool, and eventually became home to several species of rare lichens (Koehler and Keeley, 2005). By the 1960s experiments showed that low-growing Sedum plants could establish on relatively shallow, gravel-covered roofs and the concept of extensive green roofs was emerged (Herman, 2003).

Fig. 1.16 Berlin Grunewald (Source: Earth Pledge,2005)

According to Liesecke (2003), 90% of green roofs in Germany are extensive greening. Naturalistic plantings using sedums or meadows with spontaneous vegetation are the most commonly used. These green roofs are initially covered with mats or sown and they might have supplemental irrigation at first and minimum maintenances are applied. Usually, no longer irrigation is necessary after establishment because of their mild climate and high rainfall (Fig.1.17). Moreover, using photovoltaic panels on extensive green roofs are promoted in Germany and generally, Sedum or spontaneous vegetations are also used for them rather than ornamental plants (Fig. 1.18). The above situation is probably because the green roof market has been driven by ecological concerns, energy-and cost-saving potential and the need for storm water management (Herman, 2003). Another reason for using extensive green roofs with little maintenance is that green roofs tend to be installed in large areas with no-accessible flat roofs in Germany.

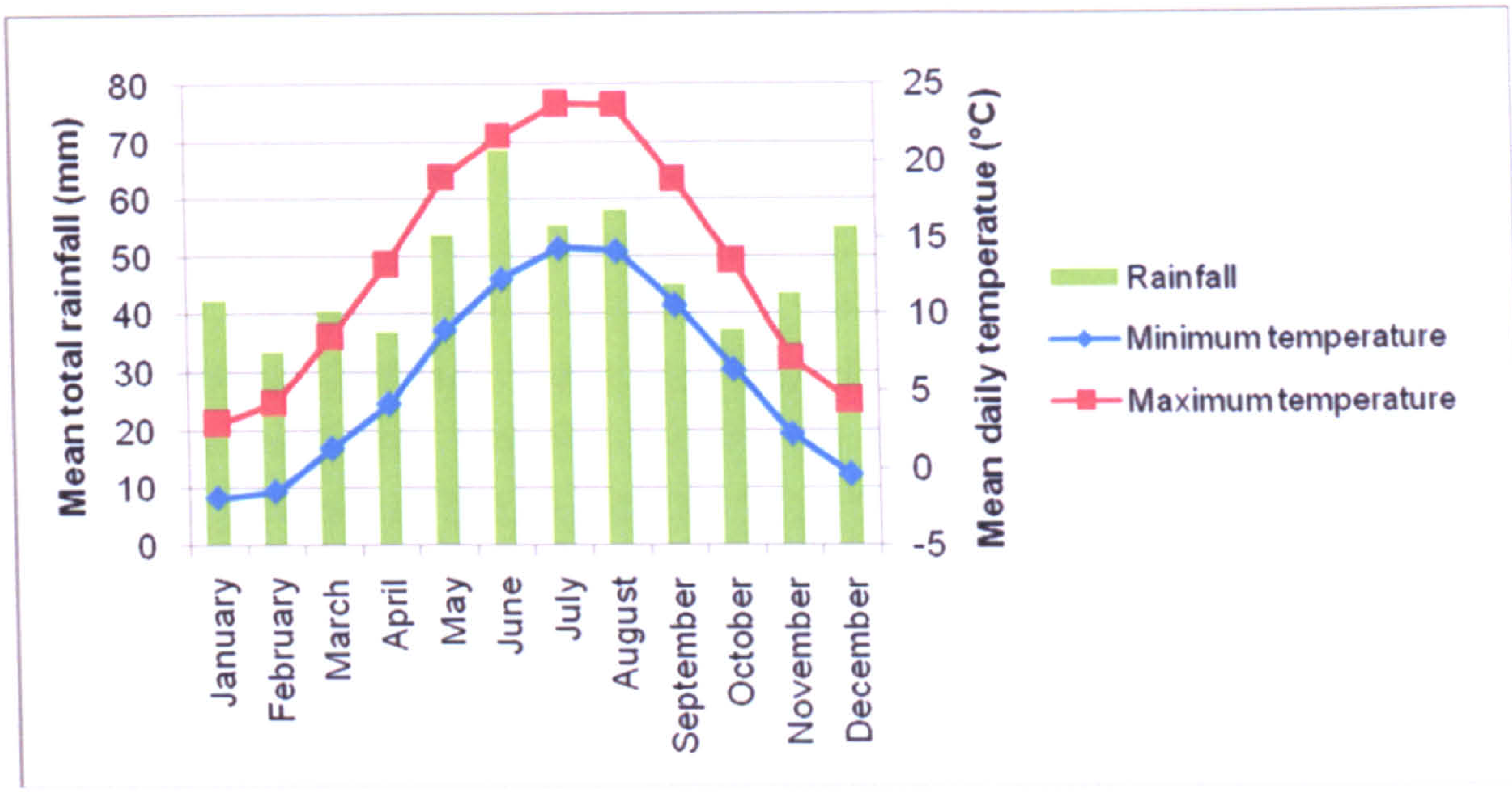


Fig. 1.17 Mean monthly rainfall and mean monthly minimum and maximum temperature over a 30-year period (1961-1990) in Berlin, Germany (Source: World Meteorological Organization)

Fig.1.18 UFA fabrik in Berlin

In Germany, an independent non-profit organization FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, Society of Landscape Development and Landscape Design) was established by scientists, contractors, gardeners, and government representative to develop universal standards for construction and quality of green roofs in 1975. This organization provides the basic tool for the construction of reliable and high quality of green roofs (Philippi, 2005). Because of FLL guideline, it is clear what kind of vegetation is possible for the different conditions of green roofs in Germany. For example, they show the standard depths for different vegetations: Moss-sedum (4-8 cm), Sedum-moss-herbaceous plants (6-12 cm), Sedum-herbaceous-grass plants (10-15 cm), Grass-herbaceous plants (15-20 cm). Although formers are more commonly used, there are many good projects using sedum-herbaceous plants and grass-herbaceous plants in Germany. The green roof companies such as Zinco and Optigrün provide the products according to FLL guideline. For example, in Sedum-herbacoues-grass extensive green roof such as shown in Fig.1.19,Optigrün commonly uses following planting list: *Achillea millefolium, A. tomentosa, Allium schoenoprasum, Antennaria dioica, Anthemis tinctoria, Centaurea scabiosa, Chrysanthemum leucanthemum, Dianthus carthusianorum, Hieracium pilosella, H. x rubrum, Petrorhagia saxifraga, Potentilla verna, Prunella grandiflora, Sanguisorba minor, Saponaria ocymoides, Sedum album* 'Coral Carpet', *S. reflexum, S. sexangulare* 'Weisse Tatra', *S. spurium, Thymus montanus, T. serpyllum, Verbascum phoeniceum, Veronica teucrium, Carex flacca, C. humilis, Festuca amethystina, F. ovina* and *Poa compressa.*

Fig.1.19 Sedum-herbaceous-grass extensive green roof (Source: Optigrün)

3.2 North America

Traditionally, sod roofs were used for pioneer buildings in North America. They usually were compromised of a heavy timber structure and a sloped wood roof deck shingled with birch bark and overlain with earth on which grass was allowed to grow (Barker, 1981). Preserved sod green roofs can be seen in some museums.

Only in the past couple of years has North America experienced an increase in the number of green roofs (Werthmann, 2007). In North America, much of the technology for green roof vegetation was imported from Europe, especially from Germany but it has been necessary to adapt it to the North America context. This is mainly because climatic conditions across North America vary dramatically from northern Europe, where the climate is milder and more predictably moist (Snodgrass and Snodgrass, 2006). For example, in Portland Oregon, the rainfall during summer is very low (Fig. 1.20). Therefore, even *Sedum* spp., which is one of the most drought tolerant plant species, are not able to survive without irrigation in Portland Oregon. Whist it is possible to extrapolate some of what has been learned in Europe, other knowledge, including that about medium composition and depth and plant tolerance to extreme weather conditions, can be gained only through practical experience in North America (Snodgrass and Snodgrass, 2006). It is worth noting that spontaneous vegetations, which are widely used in Europe, are not commonly used in North America. This is because that they do not have the dearth of insects that Europe has and they are not very good looking at a time when the North American customer wants more beauty (Snodgrass, personal communication).

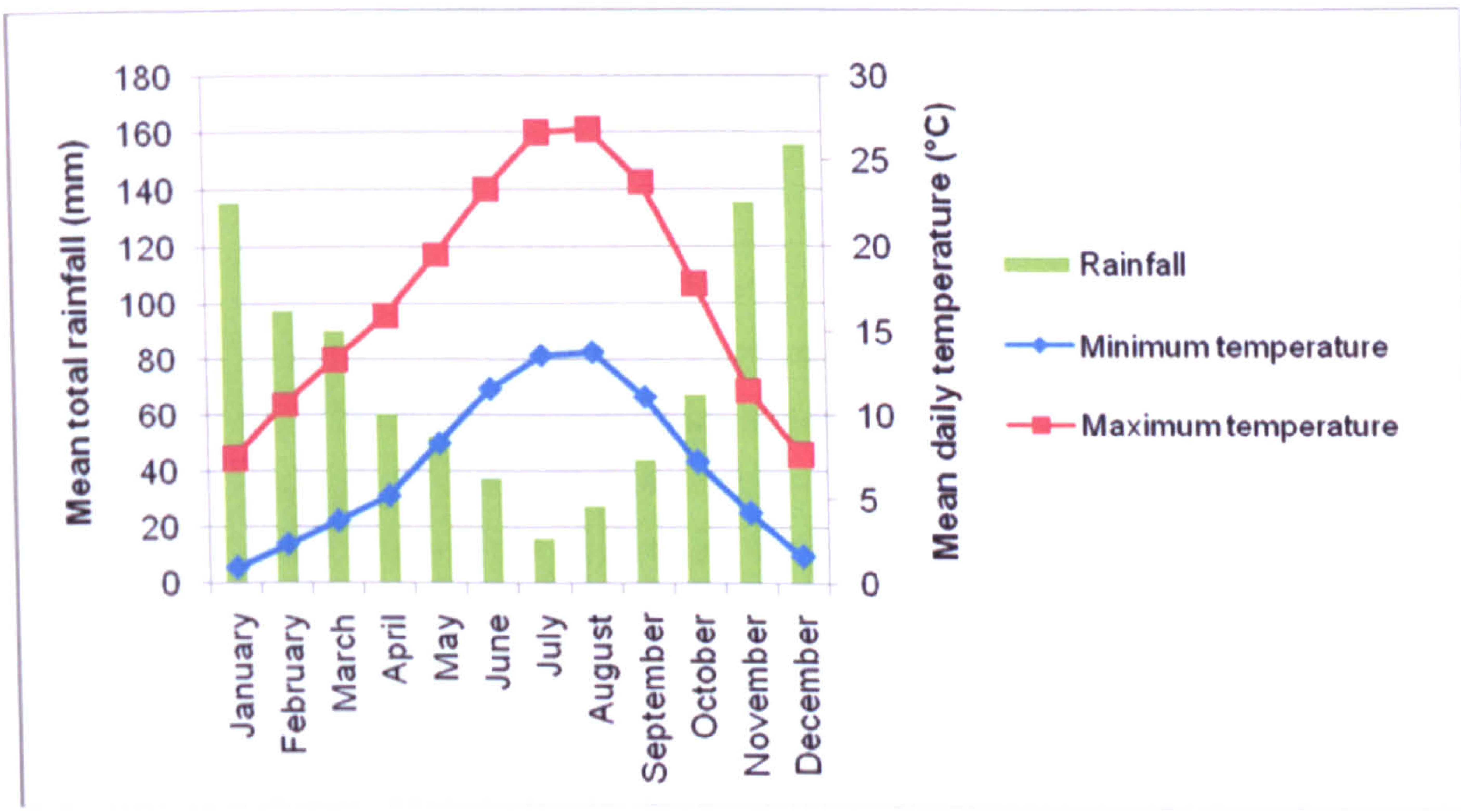


Fig.1.20 Mean monthly rainfall and mean monthly minimum and maximum temperature over a 30-year period (1961-1990) in Portland Oregon (Source: World Meteorological Organization)

Interest in using native plants for extensive green roofs is very high in the North America. Native plants generally adapt well to local climates, and the native stress-tolerant floras (particularly dry grassland, costal, and alpine floras) may have potential for extensive green roofs. Furthermore, policies for biodiversity and nature conservation may favour the establishment of locally distinctive and representative plant communities (Oberndorfer, et al., 2007). In addition, there is a vibrant native plant community in North America and green roofs seem attract a more ecological set of designers and installers by their very nature (Snodgrass, personal communication). For example, in Evansville Vanderburgh Public Library in Indiana, US, only native species, native mesic meadow prairie plant community bordered by informal group of red oak and flowering viburnum was used (Fig.1.21). The used plants are *Andropogon* *scoparius, Bouteloua curitpendula, Centaurea cyanus, Campanula rotundifolia, Carex annectans, Coreopsis tinctoria, Elymus canadensis, Liatris spicata, Phlox drummondii, P. pilosa, Sphaeralcea coccinea, Sporobolus heterolepis* (Peck, 2008).

Fig.1.21 Evansville Vanderburgh Public Library in Indiana (Source: Earth Pledge,2005)

However, many native plants have evolved in deep soils of particular structure and microbial and nutrient balance, and sometimes native plants are not able to adapt to green roof culture, because this is such an extreme environment (White and Snodgrass, 2003). It is necessary to consider their growth habit, knowledge of their hardiness, adaptability to the green roof substrate, or how much biomass they will produce (Beattie, 2004). Because native plant species which can be used for green roofs are limited and the flowering season of only native species only tends to be short, the mixture of native and non-native species are often used. For example, the green roof of the Peggy Notebeart Nature museum in Chicago successfully uses mixture of native species and non-native species (Fig.1.22). Although it is small, this green roof contains several plantings, a wetland (6 cm substrate), extensive green roof (12.5cm-15cm substrate), semi-extensive green roof (15cm-20cm substrate) and intensive green roof (20cm-25cm substrate). In the extensive and semi-extensive green roof, fewer sedums and more natives and drought tolerant hardy perennials are used. The used plants include *Achillea millefolium* 'Heidi', *A.* 'Schwellenburg', *Allium canadense, A. cernuum, Amorpha canescens, Andropogon scoparius, Anemone patens* var. *wolfgangiana, Aquilegia canadensis, Asclepias tuberosa, A. verticillata, Aster azureus, A. laevis, A. ptarmicoides, A. sericeus, Baptisia leucophaea, Bouteloua curitpendula, Buchloe dactyloides, Campanula rotundifolia, Carex bicknellii, Coreopsis palmata, Danthonia spicata, , Dianthus allwoodii, Dianthus gratianopolitanus Dodecatheon meadia, Geum triflorum, Helianthus mollis, H. occidentalis, Heuchera richardsonii, Koeleria cristata, Lavandula angustifolia* 'Hidcote', *Liatris aspera, Petalostemon candidum, P. purpureum, Phlox bifida, P. pilosa, Sedum acre, S. album, S .kamtschaticum, S. spurium, S.* 'Vera

Jameson', *Sempervivum arachnoideum, Solidago speciosa, Sporobolus heterolepis, Stachys byzantina, Thymus serpyllum, Celastrus scandens, Clematis virginiana* (Dvorak, 2003).

Fig. 1.22 Peggy Notebeart Nature Museum in Chicago, US

3.3 Switzerland

One of the oldest green roofs in Switzerland is the Moos filtration plant in Wollishofen, built in 1914 (Earth Pledge, 2005). The reason for this green roof installation was to keep the water cool during the filtration process by regulating the room temperature inside the building, into which water from the lake of Zurich was pumped and slowly filtered through a layer of sand. This substrate contains much more fine parts than the commercial green roof substrate, thus the drainage of the water is often limited on these roofs and the vegetation developed into a typical wet meadow of the region (Brenneisen, 2004a). Even though it has not been sown and the vegetation developed out of the topsoil used, the vegetation is very species-rich, currently containing 175 species, including 9 orchids and many species that are endangered or rare in the Eastern Swiss Plateau. Approximately 6000 individuals of *Orchis morio*, which is almost extinct in the surroundings of Zurich, can be found (Brenneisen, 2005b).

Fig. 1.23 Moors filtration plant in Wollishofen in Switzerland
(Source: Earth Pledge,2005)

In Switzerland, the aim of green roof instalment tends to be focused on creating habitats for biodiversity, therefore, brown roofs are widely used. This is partly because long term studies in the Basel region have been how rooftops can be transformed into near natural habitats (Brenneisen, 2005a). The aim of the work was to understand more about the bio-ecological habitat value of green roofs in Basel, where only relict populations of presently endangered species inhabit the former river banks of Rhine river, industrial brown fields and railway sidings (Brenneisen, 2003). Generally, seed mixture combining with *Sedum* spp. and drought tolerant species such as alpine plants is used in Swiss green roofs. The used species may be similar to those in Germany because their climates are similar although generally they have more rainfall in Switzerland (Fig.1.24). However, the species which attract wild bees, grasshoppers and spiders may be the priority for their plant selection in Switzerland. They tend to choose the drought tolerant species which can survive without irrigation systems and the mixture of plant species which have different height so that they create the habitats for biodiversity. The extensive green roofs in Zurich Main Station (10-30cm substrate depth), which were installed to create habitats for endangered species, the following plant species were used: *Sedum acre*, *S. hispanicum*, *S. sexangulare, S. spurium* and seeds of *Tanacetum vulgare* , *Centaurea* spp. *Allium schoenoprasum*, *Echium vulgare* and *Campanula* spp. (Earth pledge, 2005) (Fig.1.25). In another example of brown roof (13-15cm substrate depth), Rossettie Bau, the thriving habitat for spiders, beetles and grasshoppers, the designer planted minimal seed, intending that native species would colonize the area naturally (Fig.1.26). The used seed mixture includes *Achillea millefolium, Campanula rotundifolia, Cerastium spp., Chrysanthemum leucanthemum, Clinopodium vulgare, Crepis capillaris, Dianthus carthusianorum, Echium vulgare, Erigeron annuus, Euphrasia roskoviena, Globularia* spp., *Hieracium pilosella, Lactuca serriola, Leontodon hispidus, Medicago lupulina, Melilotus albus, M. indicus, Papaver rhoeas, Petrorhagia saxifraga, Plantago lanceolata, Potentilla argentea, Prunella vulgaris, Rosmarinus officinalis, Salvia pratensis, Scabiosa columbaria, S. acre, S. reflexum, S. sexangulare* (Earth pledge, 2005).

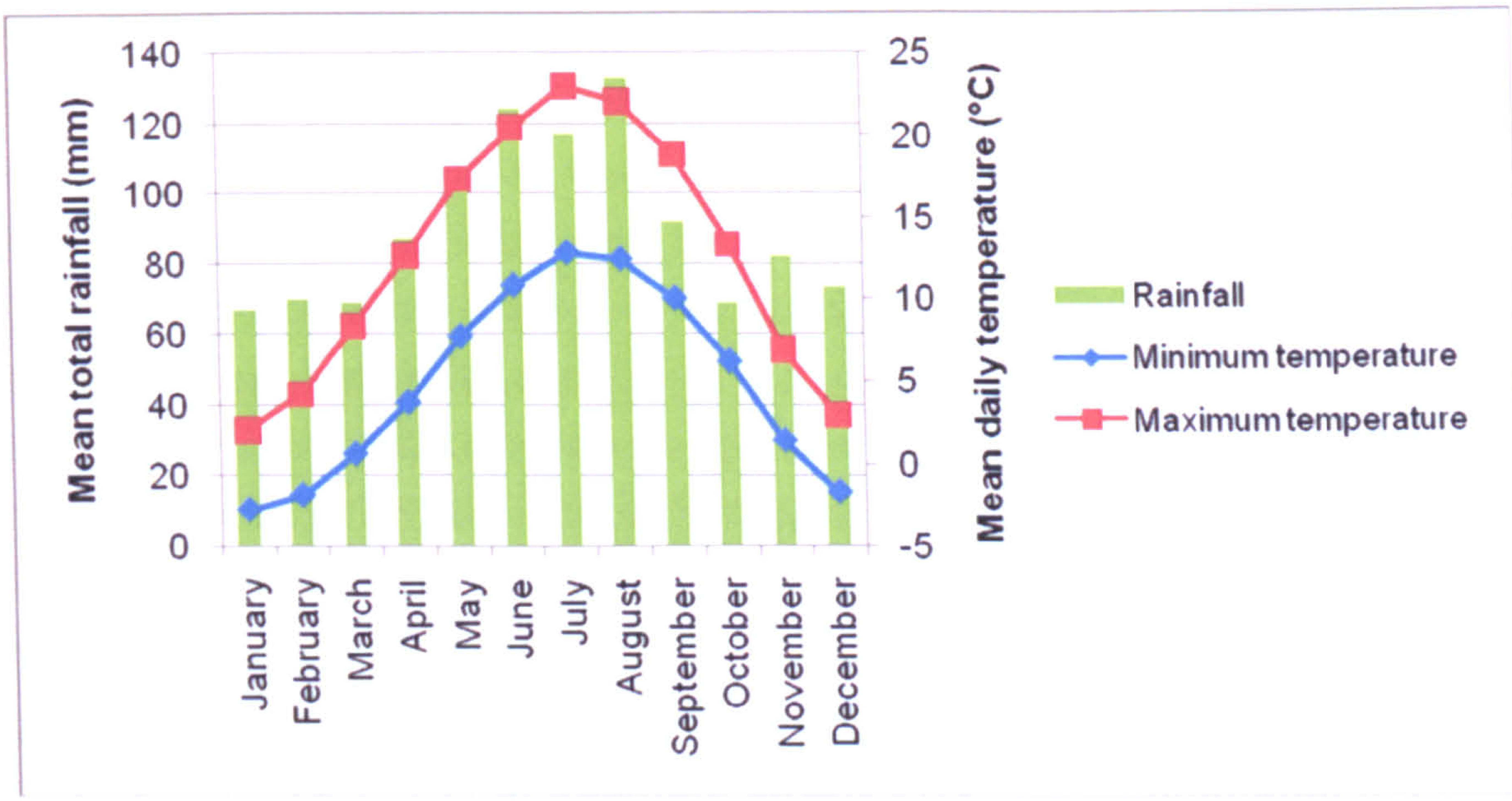


Fig. 1.24 Mean monthly rainfall and mean monthly minimum and maximum temperature over a 30-year period (1961-1990) in Zurich Switzerland (Source: World Meteorological Organization)

Fig. 1.25 Zurich Main Station (Source: Earth Pledge,2005)

Fig. 1.26 Rossettie Bau in Basel

3.4 United Kingdom

There is a long history of green roofs in the UK (e.g. Derry and Toms, installed in 1938), however, it was from 1970s that more green roofs have been installed for the recreation and aesthetic enhancement for the buildings, especially in office buildings. One of the oldest extensive green roof examples in the UK is on the 'Scottish widows' building in Edinburgh designed by Sylvia Crowe in 1976. On this green roof, low shrubs and heather such as *Cotoneaster conspicuous* 'Decorus', *Hedera helix, Calluna alba pilosa* were planted on 10cm-20cm of silt loam with peat. It is a successful example of 'natural planting', using not only native species but also many ornamental plant forms (English Nature, 2003, Scrivens, 1980). The recent upsurge in interest for extensive green roofs are (referred to as the 'Third wave'), follows from the initial ventures in the 1930s and the first interest in environmental building in the 1970-80s (Frith and Farrell, 2003).

Fig. 1.27 Scottish Widows in Edinburgh (Source: Johnson and Newton,1993)

During the late 1990s, there was a growing interest in the use of green roofs in London as mitigation for key species associated with London Biodiversity Action Plans (Gedge and Kadas, 2005). Currently, an important driving force in establishing green roofs in London is to create habitat for the Black redstart (*Phoenicurus ochruros*), which is a rare breeding bird reliant on old vacant lots and brown land (Gedge, 2003). A partnership project between Stephan Brenneisen in Basel, and Dusty Gedge of Livingsroofs.org, titled 'The UK + CH science and technology transfer project' started informally in 2001 and this developed a shared knowledge and vision of urban green roofs from a non-commercial base (Gedge, 2005). Therefore, same as Switzerland, many brown roofs were installed in London. For example, Laban Dance Centre on a brownfield along the Thames in London, which was designed specially for black redstarts and invertebrates, no intentionally deposited seeds or plants (Earth Plege, 2005) (Fig.1.28).

Fig. 1.28 Laban Dance Centre in London (Source: Kadas,2006)

However, brown roofs tend to have little vegetation and some people might think that there are weeds and gravels on the roofs. In Switzerland, these brown roofs have been well accepted by publics, however, it seems that people prefer more flowering green roofs in the UK (Gedge, personal communication). Dunnett (2006a) discussed the issue of reconciling aesthetics with ecology of brown roofs. Increasing the flowering component of vegetation to maximize colourful effects can increase acceptance in visible and accessible locations. The good example of combination of aesthetics green roof and brown roof can be seen in The Office Group building in King's Cross in London (Figs. 1.29-1.30) (Livingroofs.org, 2007). The flowering meadow is used in the part of aesthetic green roof and for brown roofs, the various substrate depths with dead branches to create habitats for birds and invertebrates.

Figs. 1.29-1.30 The Office Group building in King's Cross, London

(Photographs: Livingroofs.org)

In the UK, monocultures of Sedum spp. are still most commonly used. However, compared to the continental Europe climate and most of areas in North America, the climate of the UK is generally less extreme with relatively warm winters and a greater likelihood of regular light rainfall throughout the summer (Fig.31) (Dunnett and Nolan, 2004). This means that some plants which cannot survive on the green roof in the other countries might survive in the UK. There is the great potential to grow wide range of plants on roofs in the UK. On the extensive green roof of 10 cm substrate in the office building in Sheffield, *Armenia maritima* 'Alba', *Calamintha nepeta, Dianthus deltoides, Festuca glauca, Festuca scoparia, Gaura lindheimeri, Gypsophila repens* 'Alba', *Kniphofia* 'Border ballet', *Limonium platyphyllum, Nepeta racemosa* 'Walker's low', *Nepeta*× *faassenii, Origanum laevigatum* 'Herrenhausen', *Salvia*× *sylvestris* 'Blue Queen', *Stachys byzantina* were successfully grown over 6 years without irrigation (Fig.1.32). Probably some of these species would be difficult to survive at 10 cm substrate without irrigation in the other countries.

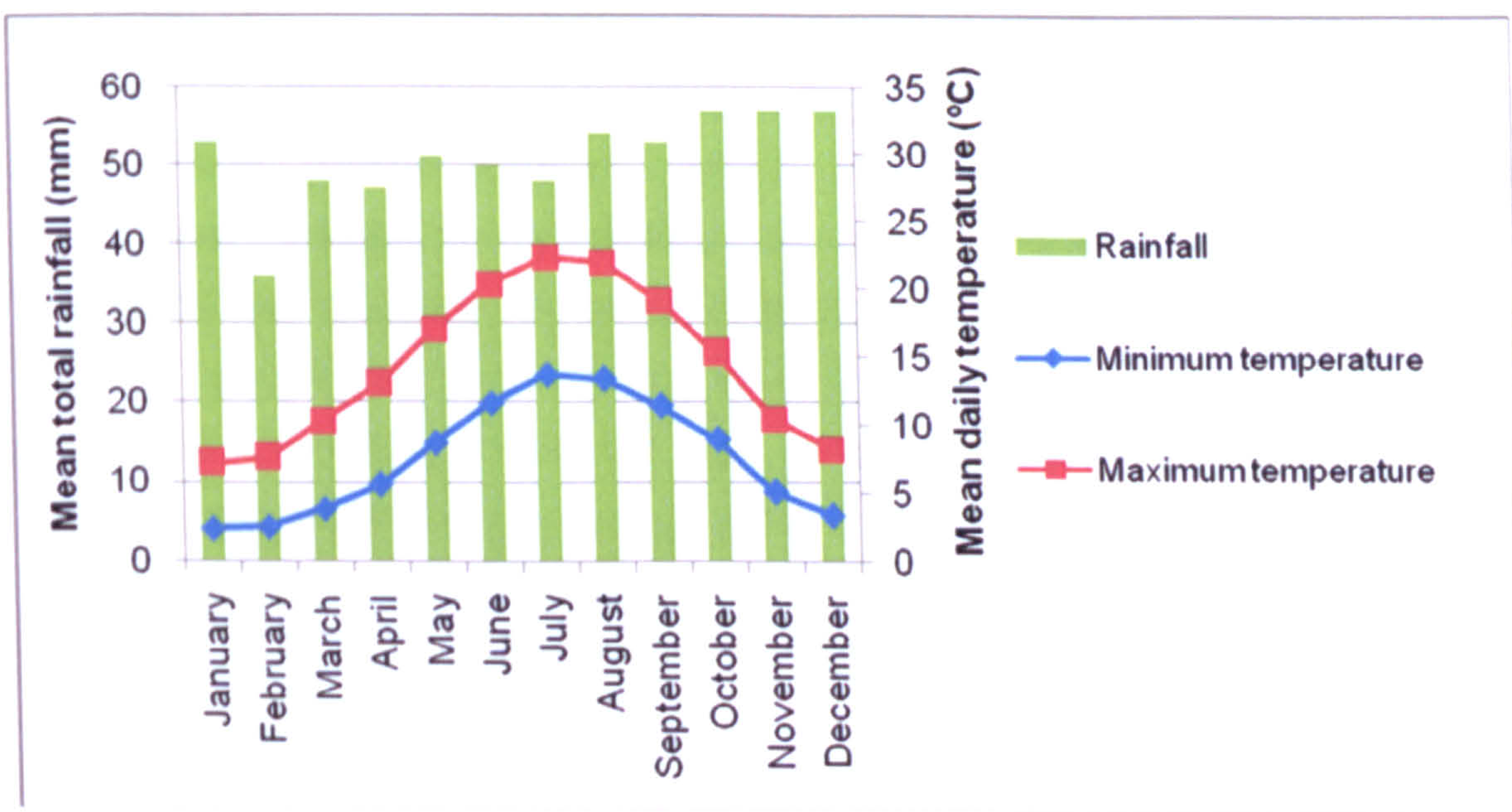


Fig. 1.31 Mean monthly rainfall and mean monthly minimum and maximum temperature over a 30-year period (1961-1990) in London, UK (Source: World Meteorological Organization)

Fig. 1.32 Office building (Ark DM) in Sheffield

Moreover, the UK has a long tradition of domestic horticulture, with a relatively high interest amongst the public in the cultivation and care of plants. Roofs and other surfaces that are not directly connected with the underlying soil represent new opportunities for such domestic culture (Dunnett, 2004a). There are several small scale green roofs using high diversity of plants. For example, the extensive green roof was installed by Nigel Dunnett in his garden shed. At 10 cm of substrate on extensive green roof, a mix of commonly available alpine plants such as *Thymes, Dianthus, Armeria*, together with other seed raised alpines dry-tolerant short herbaceous plants and grasses were planted (Dunnett, 2006b) (Fig.1.33). Domestic green roofs are recommended through the organizations and they provide the design guide leaflet and they introduced the case studies of small scale green roofs. They recommend the following species for 5 cm-10 cm substrate, *Lotus corniculatus, Primula veris, Campanula rotundifolia, Hieracium spp., Hippocrepis comosa, Anthyllis vulneraria, Galium verum, Helianthemum nummularium, Sanguisorba minor, Scabiosa columbaria, Thymus polytrichus* and for greater depth (10-15 cm substrate), *Knautia arvensis, Centaurea scabiosa, Origanum vulgare, Echium vulgare* (Gedge et al,2007).

Fig. 1.33 Extensive green roof in the garden shed designed by Nigel Dunnett

3.5 Sweden

Traditionally, turf extensive green roofs were used in the Scandinavian countries (Fig.1.34). They are made of birch bark (functioned as the sealing membrane), the twig layer (as the drainage) and turf cut from a meadow (as the insulation) and these materials are cheap and functional. *Sedum, Sempervivum* and *Jovibarba* were planted for the reinforce effect. However, grass roofs needed regular maintenance; the grass vegetation had to be cut and spontaneously established trees had to be removed. Their lifetime was limited, and they needed to be changed after twenty years, mainly due to decomposition of the sealing birch-bark layer (Emilsson, 2003).

Fig.1.34 Traditional extensive green roof in Fredriksdal garden in Helsingborg, Sweden

As time goes on, the number of these roofs decreased since alternative materials have been developed. However, because of concern over the deteriorating environment of cities, and increasing the aesthetic value of the building, modern green roofs began to be built in Sweden from the 1980s (Emilsson, 2003). Spontaneous vegetation and *Sedum* spp. are frequently used for extensive green roofs in Sweden. Probably, this is because green roofs tend to be installed because of ecological concerns, the same reason as Germany. Also, in the author's point of view, Swedish houses are well matched with these vegetations. In Sweden, green roofs are mainly applied as prefabricated vegetation mats, which is generally one of the most expensive ways to vegetate buildings but also a method that has a low risk of failure and that ensures instant high plant cover (Emilsson and Rolf, 2005). Semi-extensive green roofs or grasses are used very seldom in Sweden due to national fire restrictions limiting the use of any material that can spread fire (Boverket, 2002). For example in the building expo Bo01 in Malmö, which involved planning tools that strongly encouraged thin vegetated roofs, Sedum green roofs are mostly used (Fig.35).

Fig. 1.35 The building expo Bo01 in Malmö

Interest of using moss for extensive green roofs is high in Sweden, although there are a few examples of moss green roof right now. 19 species of moss, which have high water holding capacity, are demonstrated in Augustenborg Botanical Roof Gardens in Malmö and the biodiversity of mosses and the development over time of the richness of these species are being studied (Fig.1.36) (Lundberg, 2005). In GreenZone Ford Dealership Umea in Northern Sweden, moss tile mats as well as re-vegetated sedum were used (Velazquez, 2008) (Fig.1.37).

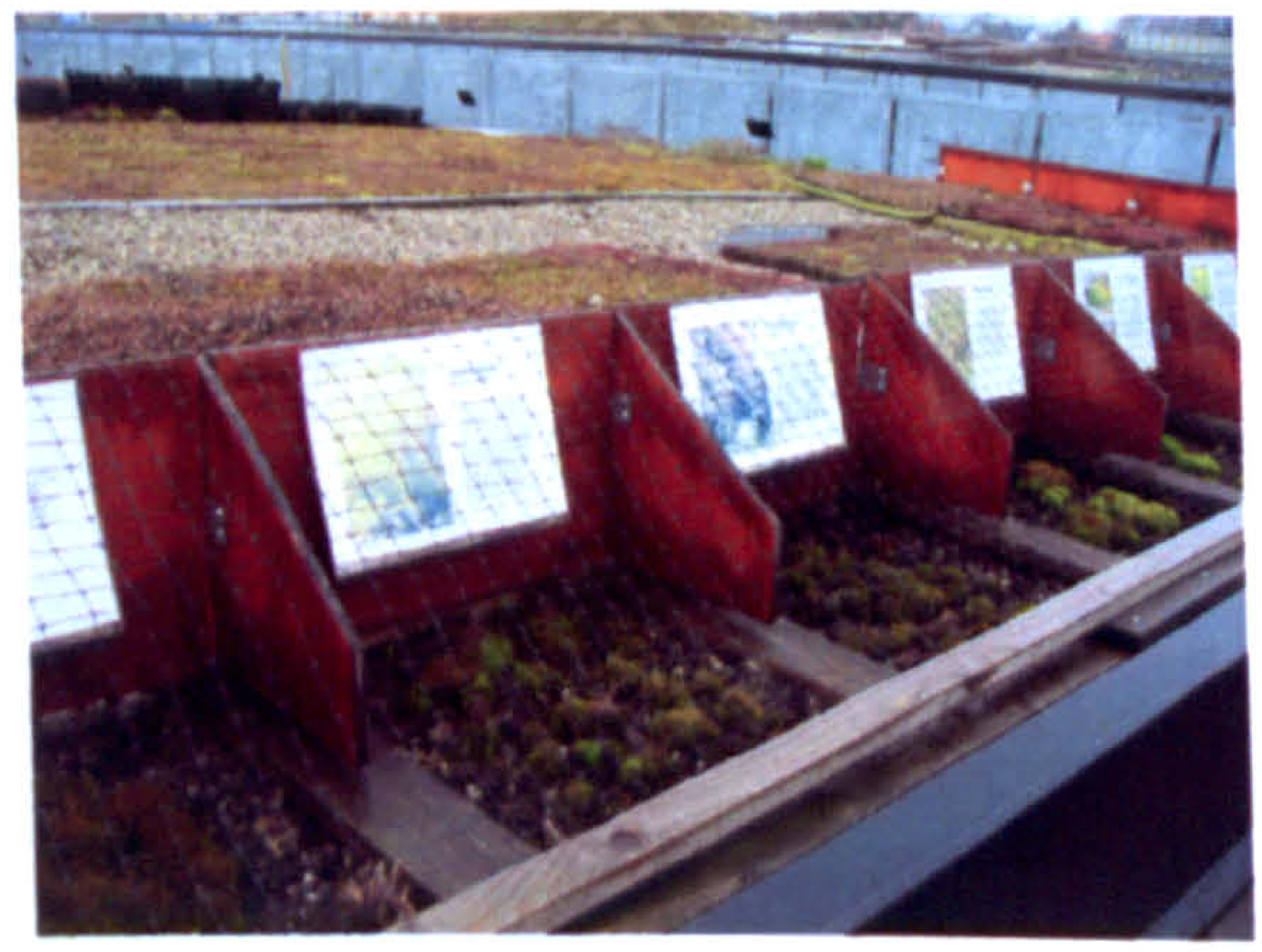


Fig. 1.36 Demonstration of Plant selections in Augustenborg Botanical Roof Garden in Malmö, Sweden

Fig. 1.37 GreenZone Ford Dealership Umea in Northern Sweden

The climate is less extreme in Southern Sweden compare to continental Europe, such as Germany, however, the winters are slightly cooler (Emilsson and Rolf, 2005). Winters in Malmö can get down to -10ºC, sometimes 15ºC (Garbutt, 2005) (Fig.1.38). However, overall, the appropriate plant species for Sweden are similar to those in continental Europe. To demonstrate ideas for attractive extensive green roofs for different purposes, several types of green roofs are shown in the Augustenborg botanical roof garden in Malmö (Fig.1.39). At 15cm of depth of substrate, following plant species are grown in Augustenborg botanical roof garden. *Achillea millefolium, Agrostis capillaris, Allium schoenoprasum* var. *alvarense*, *Antennaria dioica, Anthemis tinctoria, Anthoxanthum odoratum, Armeria maritima, Briza media*, *Bromus hordeaceus, Campanula rotundifolia, Centaurea jacea, Cichorium intybus, Deschampsia flexuosa*, *Dianthus arenarius*, *D. deltoides*, *Festuca ovina*, *Fragaria vesca*, *Galium verum*, *Helianthemum nummularium Helichrysum arenarium*, *Hieracium pilosella*, *H. umbellatum, Hypericum perforatum, Hypochoris radicata*, *Jasione montana*, *Knautia arvensis*, *Koeleria glauca*, *Leucanthemum vulgare*, *Linaria vulgaris*, *Lotus corniculatus*, *Luzula campestris*, *Lychnis viscaria*, *Origanum vulgare*, *Plantago media*, *Poa alpina*, *Polypodium vulgare*, *Potentilla argentea*, *P. tabernaemontani*, *Prunella grandiflora*, *Pulsatilla vulgaris*, *Rumex acetosella*, *Saxifraga granulata*, *Silene uniflora*, *S. vulgaris*, *Solidago virgaurea*, *Thymus serpyllum*, *Verbascum nigrum*, *Veronica spicata*, *Vicia cracca*, *Viola canina* and *V. tricolor* (Augustenborg Botanical Roof Garden, 2008). In addition, several types of green roofs are demonstrated in Augustenborg Botanical Roof Garden. Some of the examples are follows: a gravel garden which was designed to create habitats for biodiversity (Fig.1.40), small mounds covered with sedums with different depths of soil from 3-40cm and with bamboo sticks with climbers (*Parthenocissus* and *Fallopia baldschuanica*) (Fig.1.41), a hill was made of polystyrene to reduce the weight and covered by grass and dry grassland species (Fig.1.42) (Garbutt, 2005).

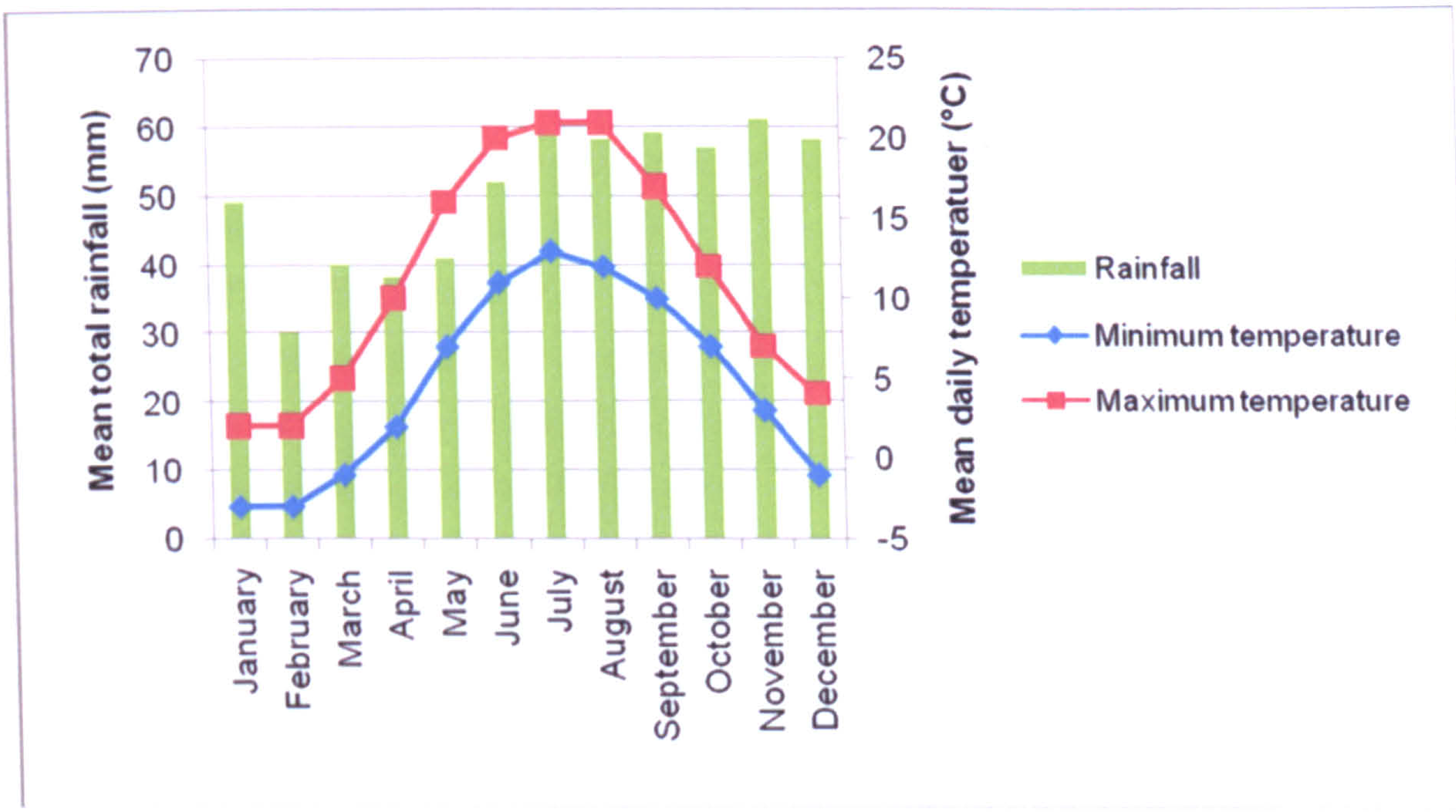


Fig.1.38 Mean monthly rainfall and mean monthly minimum and maximum temperature over a 30-year period (1961-1990) in Malmo, Sweden (Source: World Meteorological Organization)

Fig.1.39: Demonstration of Plant selections in Augustenborg Botanical Roof Garden in Malmö, Sweden (Left: Moss, Right: Forbs)

Figs 1.40-1.42: Gravel garden for biodiversity (Left), Sedum and climbers (Centre) and Meadow hill (Right) in Augustenborg Botanical Roof Garden in Malmö, Sweden

3.6 Japan

Similarly to the use of Scandinavian green roofs, the aim of using plants on the traditional green roofs in Japan was the reinforcement of the roofs. However, the big difference between the Japanese roofs and the Scandinavian roofs is that the plants grow only on the top of the thatched roof in Japan (Figs.43-44). Typical species include *Iris tectorum, Lilium auratum, Hemerocallis fulva* var. *kwanso, Allium tuberosum, Selaginella tamariscina* and *Platycodon grandiflorus*. These plants are drought tolerant and their roots develop quickly. *Iris* spp. is the most commonly used because they were treated as the charm for the fire protections. These traditional extensive green roofs were very popular in Edo period (1603-1867) and these extensive green roofs still can be seen in the Northern parts of Japan (Watari,1991).


Figs. 43-44: Traditional green roofs in Japan (Source: Watari, 1991)

Extensive green roofs have been introduced from Europe, especially from Germany, to Japan in the 1990s. Since 1990s, the number of Sedum green roofs increased dramatically. *Sedum* spp. commonly used for Japanese extensive green roofs are *S. mexicanum, S. oryzifolium, S. makinoi* and *S. japonicum*. Generally, native *Sedum* spp. are used so that they can stand high temperature in summer. The Imperial hotel in Tokyo installed the Sedum green roof and created patterns using three kinds of Sedum spp. (*S. mexicanum, S. oryzifolium, S. japonicum*) (Fig.1.45). However, according to the investigation of vegetations for newly installed green roofs by Ministry of Land, infrastructure, transport and tourism (2006), the number of newly installed sedum green roofs stopped rising. One of the reasons is that Japanese climate; they have rainy season in summer (Fig.1.46) and *Sedum* spp. tend to have the root rot when they have a lot of rain in high temperature especially if they do not have good drainage (Iijima, 2001). Therefore, it is important to choose *Sedum* spp. which can tolerant of both high rainfall and high temperature, such as *S. kamtschaticum*. Another reasons is that the research showed that *Sedum* spp. were not effective for mitigation of the urban heat island because of low transpiration, which is one of the most important environmental benefits to install green roofs in Japan (Yokoyama, 2005). In addition, some people started to think that *Sedum* spp. are not very suitable for Japanese green roofs because they have tradition of using native trees and stones in the gardens and the use of succulents may be not widely accepted in their culture. Same as North America, there are a few examples of spontaneous green roofs. Japanese people tend to require more than weeds for green roofs because they pay extra money. There is one example of green roof using spontaneous vegetation, Chihaya Hoshi to Shizen Museum in Osaka and it is blend with the surrounding well (Fig.47). However, there are negative reputations as well; some people are not happy to stay under the weeds.

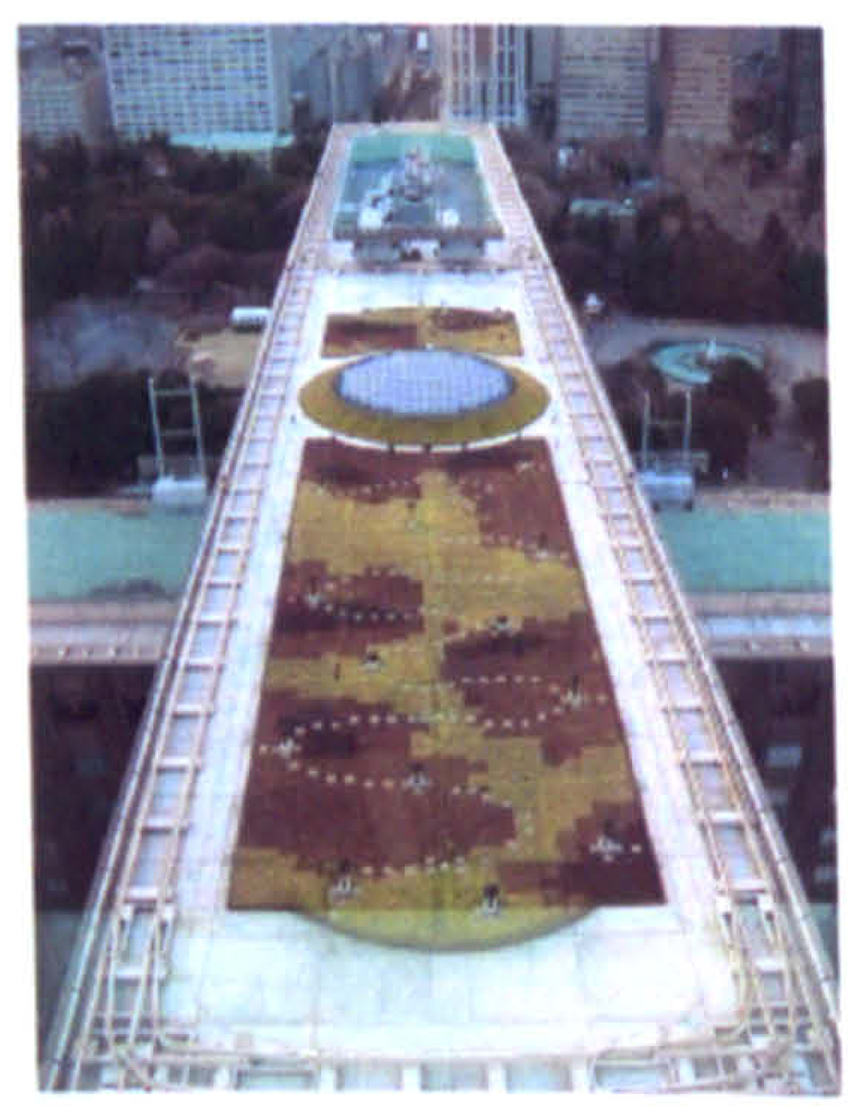


Fig.45 Imperial hotel in Tokyo, Japan

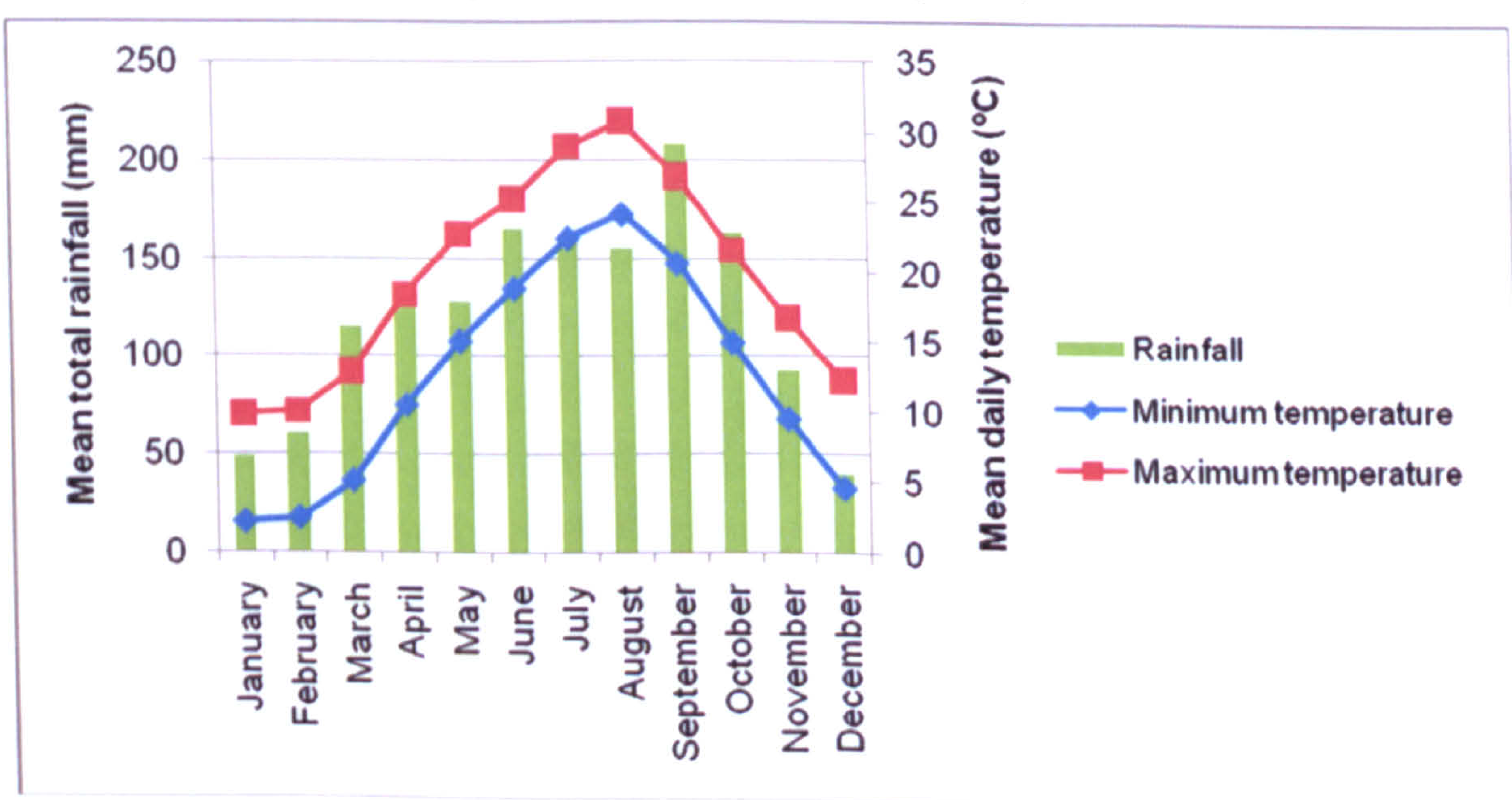


Fig.1.46 Mean monthly rainfall and mean monthly minimum and maximum temperature over a 30-year period (1961-1990) in Tokyo, Japan (Source: World Meteorological Organization)

Fig.1. 47 Chihaya Hoshi to Shizen Museum in Osaka, Japan
(Source:Nikkei Architecture, 2003)

Since many roofs are accessible in Japan, aesthetics and designed landscape are important factors and generally, it is required to use many ornamental plants. The species for annual bedding such as like Pansy are often used, although they require high maintenance (Fig 48). In a recent good example, Tajima Saitama Factory installed 2,000 m^2 extensive green roof. The soil depth was limited to 10 cm because the load-baring capacity of the building was restricted to 80 kg/m^2. In large areas, Sedum species are used, however, a variety of plant species were used in the designed of leaves (pointed by the arrow in the picture) (Fig.1.49) They have irrigation systems in these areas only. The used species were *Abelia* x *grandiflora* 'Sunrise', *Acanthus mollis, Achillea* spp., *Acorus gramineus, Ajuga* spp., *Allium* spp., *Ardisia japonica, Armeria maritima, Bletilla striata, Buddleja* spp., *Carex oshimensis* 'Evergold', *Chamaecyparis pisifera* 'Filifera Aurea', *Chamaemelum nobile, Chrysanthemum pacificum, Convallaria majalis, Cortaderia selloana* 'Pumila', *Cotoneaster glaucophyllus, Crocosmia* x *crocosmiiflora, Cytisus* x *spachianus, Dianthus* spp., *Erigeron* spp., *Euonymus fortunei* 'Emerald 'n' Gold', *Farfugium japonicum, Festuca glauca, Gazania rigens, Hakonechloa macra, Hedera helix* 'Glacier', *Helleborus* spp., *Hemerocallis* spp., *Heuchera sanguinea, Hosta* spp., *Hypericum calycinum, H.* x *moseranum* 'Tricolor', *Juniperus chinensis* 'Saybrook Gold', *J. conferta* 'Blue Pacific', *J. horizontalis* 'Wiltonii', *Kniphofia* spp., *Lampranthus spectabilis, Lantana montevidensis, Leucothoe catesbaei, Lavandula* spp., *Lippia repens, Liriope platyphylla, L. muscari*, Variegata', *Lysimachia punctata, Lythrum anceps, Ophiopogon japonicus, O. planiscapus, Oxalis articulata, Pennisetum* spp., *Phlox paniculata, P. subulata, Pleioblastus fortunei, Polygonatum* *odoratum* var. *pluriflorum, P. capitatum, Potentilla* spp., *Reineckea carnea, Rosmarinus officinalis, Rudbeckia* spp., *Sasa veitchii f. minor, Sedum album* 'Coral carpet', *S. kamtschaticum, S. reflexum, Spirea* 'Magic Carpet', *Stipa spp., Thymus longicaulis, T. serpyllum* ssp. *quinquecostatus, Trachelospermum asiaticum, Tradescantia pallida, Vinca major, V. minor, Verbena tenera* and *Zephyranthes candida* (Kodansha, 2006). Most of these plant species are commonly used for semi-extensive green roofs in Japan and they can stand the high temperature as well as drought.

Fig.1. 48 Toshima city office in Tokyo

Fig.1. 49 Tajima Saitama Factory in Saitama, Japan (Source: Tajima-roofing, 2008)

3.7 Summary

Traditionally, turfs and/or spontaneous vegetations were used for extensive green roofs in many countries. The aim of early green roof instalment tended to be function such as insulations and sometimes it was not intended to have plants on the roofs. On the contrary, contemporary extensive green roofs have been installed mainly because of environmental improvement. Extensive green roofs became popular from 1990s in most of countries. Use of extensive green roofs started early in Germany and their technologies as well as plant selection influenced other countries. Central and Northern European flora has been well trialled (Dunnett and Kingsbury, 2004a) and similar herbaceous perennial plants and grasses are used for extensive green roofs in European countries. Liesecke (2003) also mentioned that there should not be big difference for plant selection for extensive green roofs between European countries. However, it is still necessary to choose the appropriate plants and their establishment to adapt their microclimate. For example, the areas where they have high rainfall with low temperature, green roofs should have the good drainage. Also, in Mediterranean countries, it is required to have irrigation during the summer and expand the plant selection to adapt their climate (Liesecke, 2003). In other countries such as North America and Asian countries, some plant species from European countries can be used, however, it is necessary to investigate other plants including native species which can perform well in their climate. Not only climate, but also their culture, preference of clients, the main aim of green roof of instalment may influence the used vegetation types. Even though same Sedums, the planting design is different from different countries; *Sedum* spp. tend to be used with spontaneous vegetations in Europe, especially to create the habitats for biodiversity whereas they are generally used to create neat and tidy appearance in North America and Japan. It seems that most of countries have tried the German green roof technologies and plant selection at first (UK green roof learned a lot from Switzerland as well) and they started to adapt them and explore their own green roofs. Therefore, the vegetation development has just started in most of countries and evaluating potentially suitable plant species for suitable for individual country is getting important.

4. Why plant selection for extensive green roofs is important?

As it was summarized above, in the vegetation development of extensive green roofs, same type of vegetations such as *Sedum* spp. and spontaneous vegetation are the most commonly used. These vegetations are successful and their worth is proven. So why might there be a need to investigate the potential of a wider range of plants on green roofs? The benefits of exploring a wider range of planting options for green roofs can be summarized as follows:

4.1 Enhance aesthetic and visual quality

Sedum mixtures or turf can be rather dull and uninteresting if used on a large scale (Dunnett, 2004b). Using a wider range of plants on roofs can improve the aesthetic and visual quality because of different flowering time and an enhancement the visual and structural diversity. Some studies using photographs of actual green roofs or video images showed that mixed planting was preferable to monoculture for the public (Nagaoka et al., 2003, Lee and Koshimiz, 2006). Moreover, mixed planting allows wider range of opportunities for green roof planting design. These facts add to the value of a building and help to attract and retain clients.

4.2 Promotion of biodiversity

A wider range of plants can promote biodiversity. For fauna, plants that provide nectar and pollen resources are especially important and in many cases plant species support specific invertebrate species (English Nature, 2003). In a study of the length of flowering period of Sedum species and Labiatae family on the green roof in Sheffield, Labiatae family such as *N.* x *faassenii* and *Origanum* showed more than four months of long flowering whereas the flowering of Sedum spp. was more limited within only one month. While both of groups of species are good sources of nectar for wild bees, mixed vegetation containing such as Labiatae species has much greater potential to provide wild bees in urban areas than the commonly used sedum-based vegetation (Dunnett et al., 2005). As was mentioned in previous sections (3.3 Switzerland), several studies showed that plant structural diversity is important for species richness and that low plant diversity (such as a Sedum monoculture) make a low contribution to invertebrate diversity (Brenneisen, 2003, Gedge, 2003, Gedge and Kadas, 2004,).

For flora, there are possibilities that rare native species may be able to grow well in extensive green roofs if they can adapt green roof environment. Therefore, green roofs could be important places for conservation. One study indicated that *Glehnia littoralias*, which is a rare species and recorded in the Red Data book, was able to survive and perform well at the depth of 25cm green roof without watering in Kanagawa (near Tokyo) Japan. The habitat of this species is the sea coast characterized by high exposure with little water, which is similar to green roof environment (Komine et al. ,2005). Also, in brown roofs, a large number of plant species occur spontaneously on roofs and there is the potential to deliberately introduce and encourage particular species of conservation concern, where this is locally appropriate (English Nature, 2003).

4.3 Maximize green roof benefits

Many studies have shown that green roofs are effective in improving the urban environment. However, these studies tend to compare between vegetated roofs and non-vegetated roofs or Sedum roofs and spontaneous green roofs and there is a little investigation of the comparison between the various types of plants and vegetations to achieve different environmental benefits.

In one study which was carried out in the tropical climate of Singapore, the different plant species showed different degree of reduction of temperature on the green roof. Surface temperatures were measured on an intensive green roof in the city over a range of materials and vegetations. Through the shading effects of plants on the green roofs, as well as the ability to consume incoming solar radiation by physiological processes within the leaves, it can be expected that the surface temperature of the roof and the heat transfer to the room beneath will be reduced. Maximum surface temperature measured beneath Raphis (a palm with dense foliage) was only 27 °C, whereas, surface temperature of an exposed paving reached a peak of around 57 °C. The surface temperatures beneath Ophiopogon (a plant with less dense foliage) were in between the two temperatures (Tan, et al., 2003) (Fig.1.50). Although they did not show the result of statistical analysis, but this result suggests that the different vegetation may contribute to thermal characteristics of green roofs in differently.

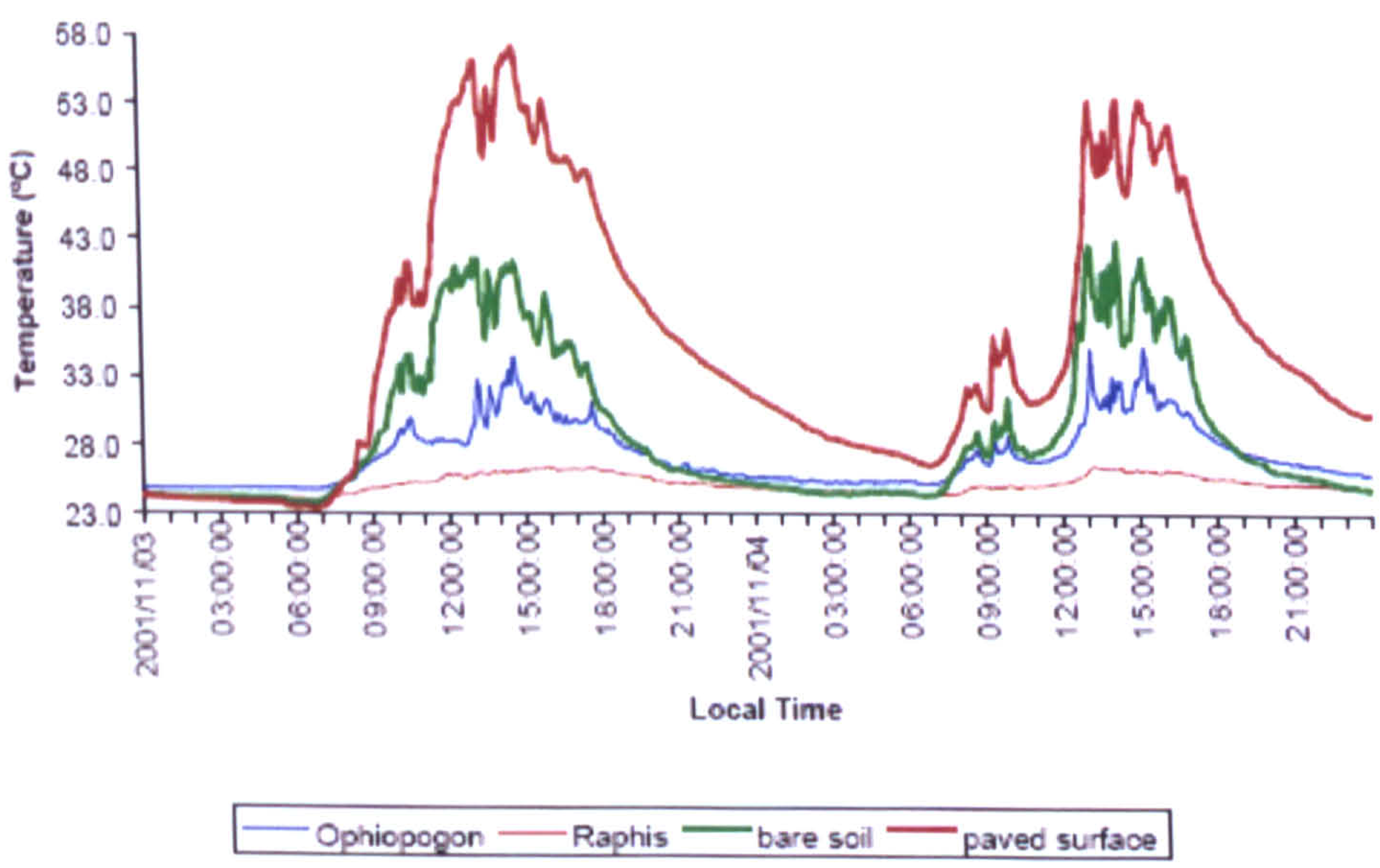


Fig.1. 50 Surface temperature measured under vegetation (Ophiopogon and Raphis), on bare soil, and paved surface on 3rd and 4th November on green roof in Singapore

Booth and Grime (2001) compared the amount of water runoff from seven different vegetation types with increasing degree of complexity. These vegetations were bare substrate, one grasses species only, one herb species only, one sedge species only, Four grass species, four sedge species, for herb species and 12 mixtures. The result showed that the composition of the vegetation was found to significantly affect both the amount of water retained and released from the system (Dunnett et al., 2005). The detail of this study will be explained in Chapter 4 (water runoff study).

It appears therefore, that differences in vegetation cover and composition can have an effect on green roof properties.

4.4 Reduction of inputs (cost, irrigation, maintenance)

Inputs for green roofs can be reduced through choosing (1) appropriate plants and vegetations and (2) appropriate establishment methods.

Exploration of the potential of plant species from naturally occurring dry habitats may have value in reducing irrigation needs. For example, semi-extensive roofs using drought tolerant species may be used as a low-input, sustainable substitute for traditional intensive roof plantings. Moreover, choosing a semi-natural type of green roof such as dry meadow, it is possible to reduce the cost for designing as well as irrigation and maintenance. In addition, high densities of sown seedlings may effectively exclude colonising weeds (Hitchmough et al,2004). If plug plants are used, choosing rapid growth plants would be less expensive because the fewer plants needed to fill a given roof area (White and Snodgrass, 2003).

As well as plant selection, establishment methods also affect inputs. It is important to remember that when a green roof is installed, all materials, including medium and plants, as well as the labourers, must be transported to the site. Especially if the building has a limited access, it is necessary to consider the way to deliver materials, such as hiring a crane (Snodgrass and Snodgrass, 2006). There are four main major establishment methods for green roofs: direct application of seed or cuttings, planting of pot-grown plants or plugs, laying of pregrown vegetation mats and spontaneous colonization (Dunnett and Kingsbury, 2004a). At present, many green roofs are installed by pot growing or plugs or pregrown vegetation mat, because of efficient establishment since the plants have well-developed root system and canopy. However, they require high initial cost. Seeds or cuttings would be the cheapest option following with pot-growing plants or plugs, and vegetation mats. Seeds and cuttings are less expensive, are less expensive, easy to carry to the site and require a small number labours, however, it takes time to cover the roof. Establishment of green roofs using seed mixture will be explained in details in Chapter 3 (germination trial).

4.5 Potential in the UK climate and culture

As it was mentioned in previous section (3.4 United Kingdom), the climate of the UK is less extreme and some plants which cannot survive on the green roof in the other countries might survive in the UK. From a cultural viewpoint, plant selection for green roofs can be also important; the UK has a long tradition of domestic horticulture, with a relatively high interest amongst the public in the cultivation and care of plants (Dunnett, 2004a).

5. Aim of study, research questions and thesis structure

Even though there are many benefits as described above, there has been very little investigation into plant selection for extensive green roofs and plant communities in the UK. This is a major research gap because plant selection and plant communities are the key factors to achieve these benefits. Therefore, the work in this thesis focused on the following objectives.

1. To identify groups of plants that have potential for use on green roofs, with regard to tolerance of rooftop conditions

2. To investigate establishment methods for diverse, attractive, flowering green roof vegetation, with attention to seedling techniques

3. To test survival and performance of a selected range of species and cultivars from the previously identified groups (annuals and geophytes) at different substrate depths, irrigation regimes and covering plants treatments.

4. To compare the green roof performance (water management and drought tolerance) between different vegetation types and drought tolerance in the different percentage of organic matter

5. To investigate the performance of plants as well as their aesthetic appeal, seasonal interest over time and what is required for maintenance (weed invasion and self-seeding)

As is shown in Table 1.2, this thesis consists of 6 chapters. The first two chapters are literature review and case studies to give an overview of the background and potential plants for green roofs from a horticultural point of view. Experimental works are described from chapter 3 to chapter 5. In chapter 3, plant performances on the roof are studied using plant screening methodology. Each experiment follows a conventional structure (abstract, introduction, materials and methods, results, discussion and conclusions). However, they are written in the format of publications for journals so that they can easily be published. The process of plant selection for extensive green roofs in this chapter is described in Fig.1.51

Table 1.2 Thesis structure

Chapter 1 Introduction	Chapter 2 Plant selection	Chapter 3 Plant performance on the roof	Chapter 4 Plant physiological study	Chapter 5 Intensive one year study	Chapter 6 General discussion
Introduction Definition and background The benefits of studying plant selection Aim of study, research questions and thesis structure	Introduction Identification of planting patterns Potential plant group Previous research for plant selection for extensive green roofs	Germination trial Annual plant species Geophytes	Organic matter Drought Tolerance Water runoff	Seasonal change Individual growth pattern and flower performance Planting design Maintenance	Survivability Potential limitation Function Aesthetic Conclusion
Literature review	Literature review	Experiment on the green roof	Experiment in the green house	Experiment on the green roof	

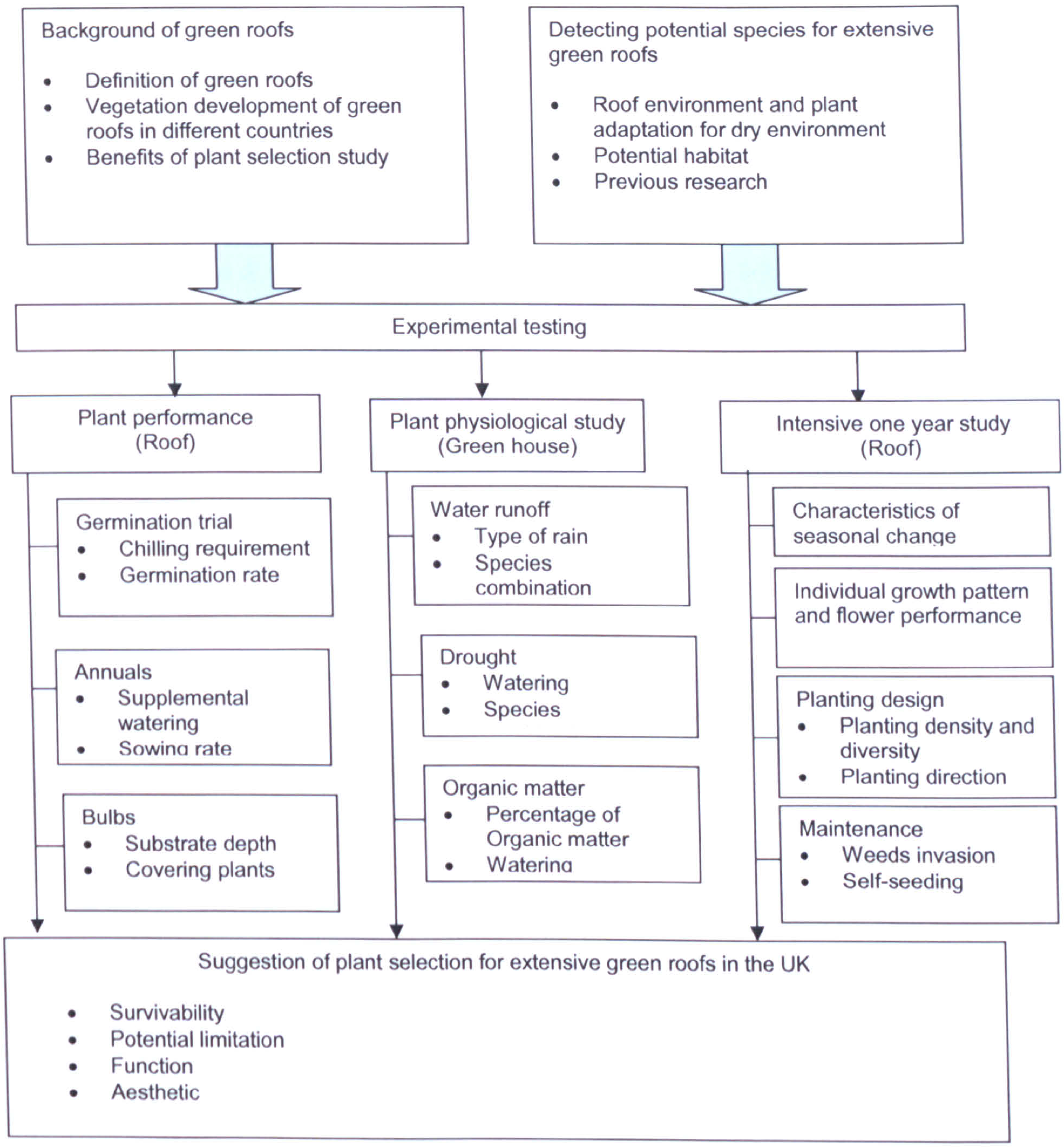


Fig.1.51 Mind map of thesis

Chapter 2 Plant selection criteria for green roofs

1. Introduction

Chapter 1 contained an overview of the vegetations of extensive green roofs, of the vegetation development in the different countries, and discussed the benefits of plant selection studies. In this chapter, plant selection criteria are explained from a horticultural point of view. Firstly, it is important to detect the limitations on plant growth on a roof environment. Then, it is necessary to understand the plant mechanisms to adapt to these harsh environments on the roofs and which plant species are more likely to survive in there. Also, not only survivability but functional and aesthetic criteria should be considered to achieve the aim of instalment of green roofs successfully. Therefore, in this chapter, following five main questions are considered.

1) What are the characteristics of roof environment? What are the problems of the roof environment for plant growth?
2) What kind of mechanisms do plants have to survive the roof environment?
3) Which groups of plants have potential for exploitation as green roof materials?
4) What is the process for plant selection to consider in terms of not only survivability but also functional and aesthetic criteria?
5) What is the previous research which is related to plant selection for green roofs?

2. Roof environment and plants development

The roof environment is unique and it can be very severe for plants. Plants must be matched to the roof location for both micro and macro climate conditions (White and Snodgrass, 2003). The general characteristics of the roof environment can be summarized as follows.

2.1 Above the ground

2.1.1 Wind

Mean wind speeds on the rooftop are generally higher than at ground level (Hitchmough, 1994d). However, wind in urban areas is more complex and the wind speed of down drafts can sometimes be greater at the bottom than at the top of tall buildings. When wind strikes a tall building, it breaks up into many swirls and eddies, as shown in Fig.2.1 (Beck,1979). The configurations of the building, protection by parapet walls on the roof, carefully considered placing of utilities associated with air conditioning can help to reduce the wind speed (Johnston and Newton, 1993). However, it may be difficult to install wind shelters for extensive green roofs, especially in inaccessible places. Generally, the wind stress is low in the central area of a roof but it is high in the corners and edges, therefore it is recommended to use the gravel and slabs for these windy places because plant growth may be difficult in these places and the heavy materials in edges hold the roof in place (Fig.2.2) (FLL 2002). Plant developments can be affected in windy environments. They include enhanced desiccation and a more extreme temperature regime for exposed tissues and direct damage by the wind. Increasing wind speed can decrease evaporation because the increased heat loss lowers leaf temperature and the water vapour presser in the leaf (Jones, 1983). Small leaves, hairy leaves, low growing species such as tussock of grasses and cushion plants are able to adapt windy environment because they can reduce boundary layer thickness (Hitchmough, 1994d, Larcher, 2003). Plant surfaces have boundary layers of relatively still air where turbulence does not occur. Here temperature and relative humidity, partly as a result of photosynthetic and transpiration process, can differ markedly from ambient levels (Schoonhoven, et al. 2005). In Fig.2.3, decrease of boundary layer resistance above differently sized leaves as function of wind velocity is shown. d= leaf dimension is parallel to the direction of air movement (Grace, 1997).

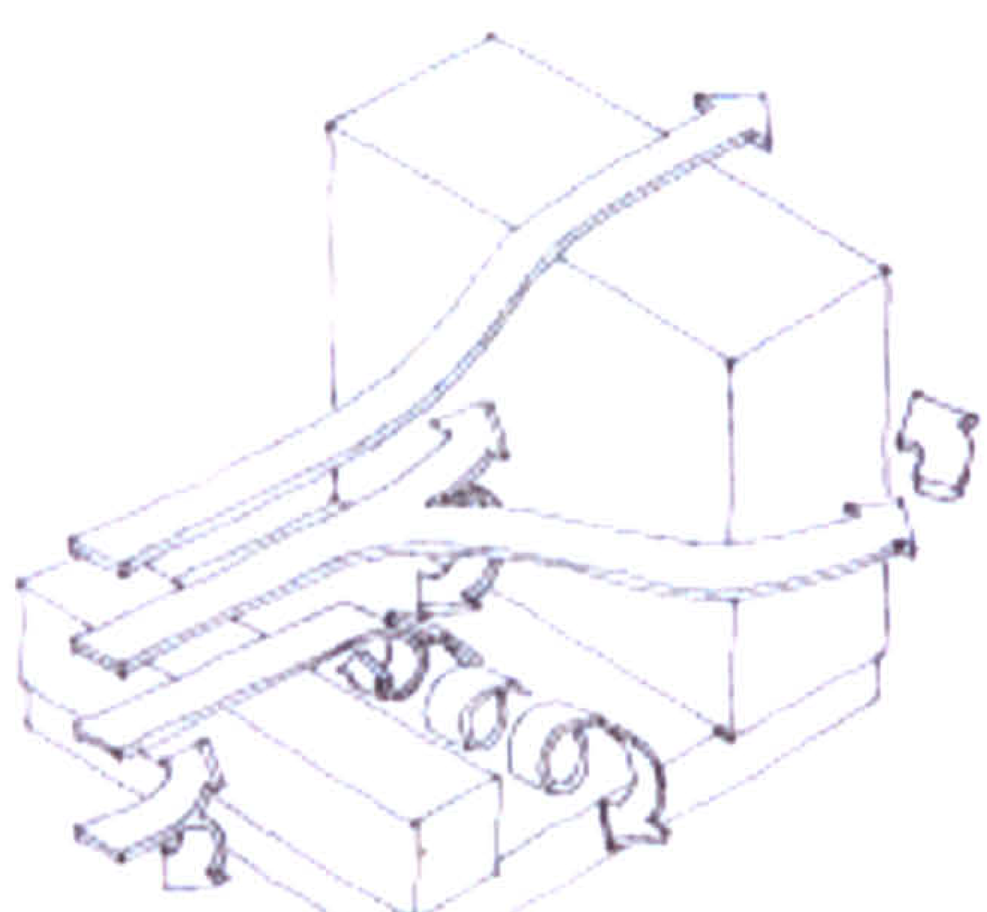


Fig.2.1 The wind movement when it strikes a tall building, Source: Beck (1979)

Fig.2.2 Using the gravel at the edge and corner of extensive green roofs

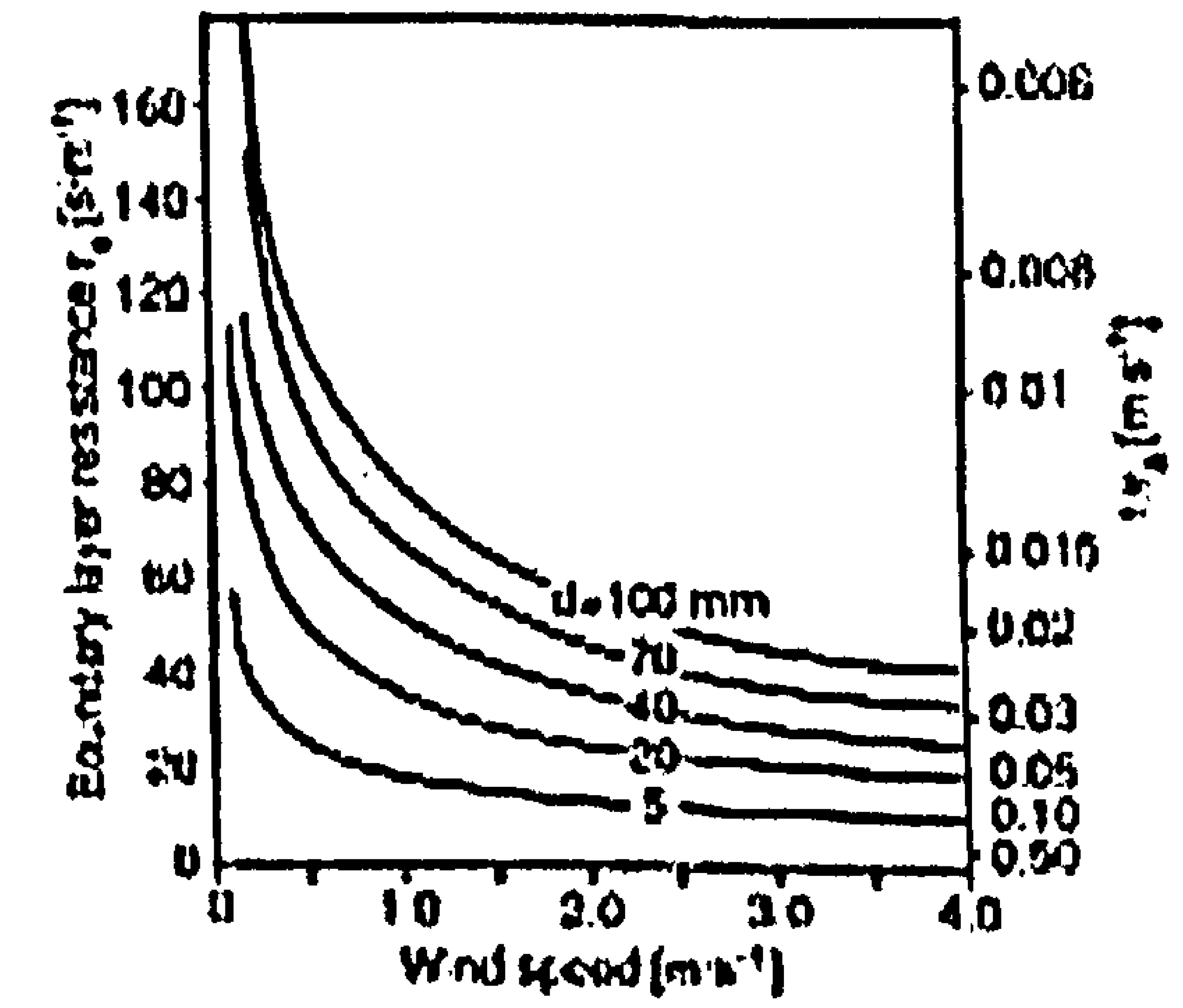


Fig.2.3 Boundary layer and shape of leaves (Grace,1997)

2.1.2 Air temperature

Generally, the temperature on the roof is higher than the ground because there is no shelter from the sun in many cases and the heat from the interior of the building may be transmitted through the roof (Johnston and Newton, 1993, White and Snodgrass, 2003). Moreover, concrete or stone buildings absorb and hold a significant amount of heat in their walls and reradiate at night (Dunnett and Kingsbury, 2004a). During cold seasons a higher temperature will be gained (Beck, 1979), therefore, the risk of plant damage from frost is significantly reduced for many green roofs (Hitchmough, 1994d). Indeed, Hitchmough (2007) showed that the air temperature on the roof was at least 4 °C higher than the ground level in early January in 2006 in Sheffield, UK. However, it appears that during hot seasons, temperature on the roof tend to be lower than the ground (Hitchmough, 2006). One of the reasons may be that mean air temperature decline by 0.6-0.7 °C for every 100m increase in altitude, consequently green roofs may experience lower daytime air temperatures than plantings at ground level, especially when combined with high mean wind speeds (Hitchmough, 1994d). In a comparison of air temperature at a ground level in the down-town area and air temperature above a roof in Tokyo, Japan in August 1998, the air temperature above the roof showed lower temperature in daytime than the ground although at night it was the opposite. The difference in the air temperature between the roof and the ground was smaller at night and at around 12:00 midnight, the air temperature above the roof was higher than the ground (Fig.2.4) (Nishikawa et al., 2000).

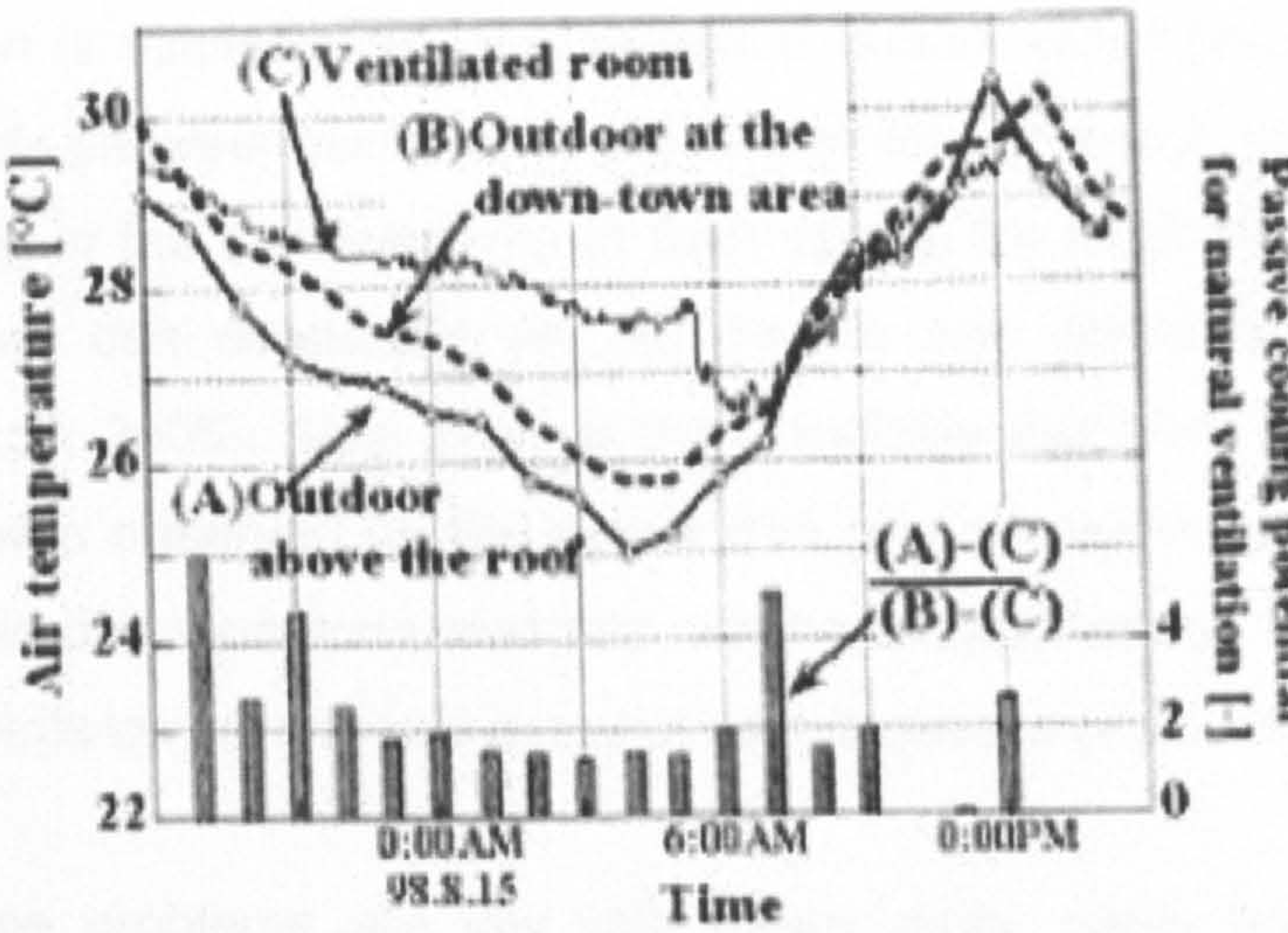


Fig.2.4 The variation of outdoor air temperature above the roof, indoor air temperature in a ventilated room and the outdoor air temperature of the downtown area (Nishikawa et al., 2000).

2.1.3 Solar radiation

Solar radiation on roofs tends to increase because of the reflection of light and open space. Increases come about via reflection of light from surfaces of high albedo resulting in leaf overheating of species not adapted to this form of double dosing (Hitchmough, 1994d). Although drought tolerant plants have mechanisms to adapt to high solar radiations (e.g. thick layer of trichomes), excess light would result in leaf death and at least damage that impairs the photosynthetic activity in water-stressed leaves (Ludlow and Björkman, 1984). Of course, solar radiation would be different depending on the location of green roofs. If there are additional building levels which intercept direct sunlight, solar radiation may be lower than the ambient at ground (Hitchmough, 1994d). Recent studies showed that a level of solar radiation also differs with the colour of roofs, for example, a light colour roof might reduce a high absorption of solar radiation (Liu and Baskara, 2003).

2.1.4 Biological factors

Green roofs can be important place for wildlife habitats, although green roofs cannot be straight substitutes for wildlife habitats at ground level because many animals cannot get to the rooftop and growing conditions are not suitable for all plants. However, many insects and birds will find suitable food and shelter and perhaps even a place to breed (Johnston and Newton, 2003).

A little information is available on how biological factors affect plant growth on green roofs. Visiting birds on green roofs could dig up and disrupt seeds, plug plants and bulb species. Birds dig in the soil substrate in their search for food and spread moss and plant parts, which can eventually end up in the rain gutter and cause clogging (Emilsson and Rolf, 2005). Also, there is the possibility that birds may spread weeds. For example, it was observed by the author that pigeons were eating the weed seed heads of *Capsella bursa-pastoris*, and this may encourage weeds to spread. However, overall, visiting birds on green roofs may not cause serious problems for plant growth.

Pest and disease problems are few with green roofs, partly because the species commonly used are not generally badly affected with particular pest problems. When diverse plant communities are used, if one species becomes adversely affected, there are always plenty of others in perfect health around, so that any problems do not become conspicuous (Dunnett and Kingsbury, 2004a). Although they are not many, some pest problems are reported. For example, aphids and/or Potter's mildew infested *Lupinus polyphyllus* on the extensive green roofs in Seattle (Martin and Hinckley, 2007). In Portland Oregon, *Sedum album* was attacked by some form of caterpillar and quickly died out (Hauth and Liptan, 2003). It was also mentioned Sedum green roofs might suffer from aphids in the UK (Gardens affairs Ltd., 2008). Hitchmough (2004c) pointed out that slugs and snails are more problematic than pest or disease in a landscape situation and probably it would be the same in green roofs. It was observed slugs by the author on the extensive green roof in Sheffield, UK. It was not serious, although they attacked *Iris bucharica*, especially when they were growing in shallower substrate (5cm) than deeper substrate (10cm). It was also observed that slugs were hiding under *Silene uniflora* after rain on the green roof in Rotherham, UK.

2.2 Below the ground

2.2.1 Substrate characteristics

In many green roofs, artificial soil or substrate is used. Artificial soil provides the same mechanical support for plants as general garden soil, however, it is versatile and has adaptability for specific requirements of plants (Tan, 2000). It is possible to provide a partially controlled and uniform soil environment. In addition, generally, artificial soil is weed free in the beginning and it may cause fewer problems of weeds than natural soil. In fact, general garden soil or top soil is not suitable for extensive green roofs because it is too heavy and too fertile. High fertility is not desirable because it encourages vigorous lush growth that is susceptible to environmental stress, whether this would be from extreme cold or drought (Dunnett and Kingsbury, 2004a). Probably, microbial activity would be less in the substrate for extensive green roofs than in general garden soil because of less organic matter. In nature, microorganisms are found in greatest numbers where food supply is most abundant in the top 5 cm of substrate, around roots, and in and around dead organic matter. Microbes can be both beneficial and harmful to plants, however, most of the microbes in organic matter are beneficial to plants. They help plants by suppressing pathogens and by enhancing plants' self-protection mechanisms (Handreck and Black, 2002). There is little study of microorganisms in green roofs. Meyer (2004) studied the use of endotrophic miycorrhiza and soil microorganisms in vegetation establishment on mineral green roof substrates. The result showed that the addition of soil microorganisms into a green roof substrate helps establish vegetation. Microorganisms aid the roots in exploiting essential nutrient and water reserves in the substrate by making them more readily available to the plants. Uniform germination, improved plant development at the young stage, as well as prolonged vegetation development on the roof can be realized.

2.2.2 Moisture in substrate

Thin, free-draining growing medium layers, evaluated temperatures, and wind combine to make roof substrate excessively dry (Dunnett and Kingsbury, 2004a). Moreover, after rain, the soil on extensive green roofs experiences rapid fluctuations between saturation and drought (Johnston and Newton, 1993). Water availability is one of the most important factors for vegetation development of extensive green roofs. According to FLL (2002), mean annual rate of water retention is different from substrate depth and vegetation types (Table 2.1). Obviously, a deeper substrate has a higher annual rate of water retention, therefore it is possible to grow more plant species and they encourage plant growth, however, they are also more hospitable for undesirable weeds. The slope of roof and the position of roof also affect the plant growth. As the gradient increases, so does the rate at which water runs off the roof. A layered superstructure with a fairly high water storage capacity and poor drainage, or the vegetation which does not require a great deal of water, will compensate for gradients of 5% of more (FLL, 2002). According to Martin and Hinckley (2007), the positive relationship between plant mortality and roof edges/corners was observed because the drought conditions were exacerbated in these areas and many plants were unable to function or survive. The mechanism of plant adaptation for drought will be explained later in this chapter.

Table 2.1 Mean annual rate of water retention of different depth of substrate and vegetation, FLL (2002)

Depth of substrate (cm)	Vegetation	Mean annual rate of water retention(%)
2-4	Moss-Sedum	40
>4-6	Sedum-moss	45
>6-10	Sedum-moss-herbaceous plants	50
>10-15	Sedum-herbaceous-grass plants	55
>15-20	Grass-herbaceous plants	60

2.2.3 Soil temperature

Soil temperature can fluctuate between very low and very high values in extensive green roofs especially in the shallow substrate. This affects plant growth and survival. Koehler (1990) showed that the thin soil on the roof of an unheated building at the Technical University of Berlin was significantly colder than that on the ground level in winter, and higher up to 5°C in summer. In another study by Koehler (2004a) in Neubrandenburg Germany, minimum temperature and maximum temperature inside a growing medium of extensive green roofs showed -13.4 °C and 44.7 °C respectively. In one study by Martin and Hinckley (2007) investigating substrate temperature in 15 cm depth of green roof in Seattle, the plants were subject to high growing medium temperatures (50-60°C) and it is even higher than the ground surface temperature. In the UK, the winter climate is mild, however, soil frost can be the problem. As it was mentioned in 2.2.1, the risk of plant damage from frost may be low on the green roofs, however, thin soil on the roof can freeze easily than deeper soils on the roof (Johnston and Newton, 1993). It was observed by the author that 5cm of depth of substrate on the extensive green roof in Sheffield UK was completely frozen more than two weeks in November 2005. If the soil freezes, it is difficult for plants to take up water because of increased transfer resistance between soil and roots and the growth of roots is inhibited (Larcher,2003). In the study of Bovin et al. (2001), the temperature of vegetated soil was monitored at root level. The results showed that minimal temperature records with 5 cm depth soil were significantly lower than 10 cm and 15 cm, especially in winter, as it is shown in Table 2.2.

Table 2.2 Daily minimum temperature and temperature variation registered throughout the experimental period 1995-1997 (Source: Bovin et al., 2001).

Substrate depth (cm)	Minimum temperature (°C)		Temperature variation (°C)	
	Oct-Nov 1995[Z]	Oct-Nov 1996[y]	Oct-Nov 1995	Oct-Nov 1996
5	-0.4 a[W]	-5.9 a	8.3 b[W]	4.5 a
10	0.9 b	-4.3 b	5.9 a	5.9 a
15	1.6 b	-2.5 c	4.7 a	7.3 a
	April 1996	April 1997	April 1996	April 1997
5	-0.4 a	-0.2 a	10.5 a	6.4 b
10	0.6 b	0.2 a	7.5 a	4.6 a
15	1.0 b	0.5 a	5.9 a	3.7 a

[Z] 23 Oct to 14 Nov 1995 mean

[Y] 12 Oct to 20 Nov 1996 mean

[X] Difference between daily maximum and minimum temperatures

[W] Means of the same column, within the same year, with the same letter are not significantly different according to LSD protected test (α=0.05).

2.2.4 Limitation of root growth

Because of the shallow substrate, plant root growth is limited in extensive green roofs. However, generally, plants found in desert climates have characteristics such as deep taproots, a widely spreading and widely spaced fibrous root system, or storage organs that resist water loss (White and Snodgrass, 2003). Deep root systems are more tolerant of drought than shallow-rooted plants because the surface soil is quickly depleted during summer droughts (Kramer and Boyer,1995). On the contrary, deep rooting plants would be not suitable for a shallow substrate (Dunnett and Kingsbury, 2004a). Shallow rooted plant species, called 'shelf plants' found growing naturally on only a few inches of soil, would be more appropriate for extensive green roofs (White and Snodgrass, 2003).

3. Mechanism to adapt dry environment

To adapt to the above harsh green roof environments, drought tolerance is the one of the important factors for plant selection. Moreover, drought tolerant mechanisms run parallel with mechanisms for other exposures such as high temperature, high radiation and strong wind. Xerophytes, the plants which can exist in dry environments, are drought tolerant because they have some mechanisms to adapt to dry conditions. These mechanisms can be divided into three types: evolutional adaptation, modulative adaptation and modificative adaptation (Larcher, 2003) and they are explained as follows

3. 1. Evolutional adaptation

Evolutional adaptation is part of the genotype and determines the habitat preference of different plant species. It includes seasonal escape, morphology and development of photosynthesis.

3.1.1 Phenology

A plant that rapidly completes its life cycle or grow during periods of favourable soil moisture can escape periods of drought (Jones, 1983). Annual species and geophytes from arid continental climates have these phonological adaptations. Annual species complete their entire life within a year. They germinate, grow and flower in the favourable season and they lie dormant as seeds in the harsh time of the year (Barber, 1954). Geophytes grow, flower and seed during cool moist seasons and then disappear into the comparative cool of the earth when the sun bakes the land in the summer (Kingsbury, 1996). The growing season is short, and where the plants need the stored energy to flower and set seed quickly in the spring (Blamey and Blamey,1979). Generally, these plants do not rely on any other physiological mechanisms for surviving in dry climates. The detail characteristics of annual plants and geophytes will be summarized in chapter 3.

3.1.2 Morphology

Many of xerophytes can limit the rate of water loss by minimizing the water transpiration through adapted morphology including following characteristics (Jones, 1983).

- Thick cuticle

A cuticle is composed of cutin and wax, anchored to the epidermis by a layer of pectin (Kramer and Boyer, 1995). Cuticular transpiration can be regarded as diffusion through a hydrophobic medium, since the water modules must pass through the cutinized layers of the outer wall of the epidermis and through the epicuticular wax lamellae. Permeability of the cuticle for water vapour is very low. Water vapour of typical value of soft leaves was 10-15 $nmolm^{-2}S^{-1}$ whereas leaves with cuticle showed 0.5-3.0 $nmolm^{-2}S^{-1}$ of water vapour because the water molecules must pass through the cutinized layers (Larcher, 2003). The function of a thick cuticle also includes protection of the plant from injuries due to wind and physical abrasion, frost and radiation, potential barrier to attack by fungi, insects and other pathogens (Martin and Juniper, 1970). Generally, cuticle of the leaves is well developed for plants living in habitats of coast and dry area plants.

- Trichomes and epidermal hair

A thick layer of trichomoes or epidermal hairs reflect light and decrease the leaf temperature. According to a study using *Encelia* spp., a desert shrub, the species with trichomoes reduced the net photosynthesis in winter and wet conditions in summer because they reflected light. However, their leaves gained a higher rate of carbon under arid conditions than the leaf could acquire without hairs. This allowed the plant to extend its growth for a longer period into the drought (Ehleringer, 1980). Stomata are often hidden beneath dense hairs or in depressions. In this way, boundary layer resistance is increased and the air outside of the stomata becomes moist, and an effective reduction of water loss can be achieved (Larcher,2003). The genera which have trichomes include Compositae, Labiatae and Polygonaceae (Ehleringer, 1980).

- High water content

Succulent plants have thick leaves and reserve water in the mesophyll of the leaves. In the rainy season, the sap of these plants circulates vigorously and growth proceeds. In dry months with high temperatures, they are dormant, slowly drawing upon stored reserves. The periods of water deficiency are overcome with endogenous water reserves (Kluge and Ting, 1978). The most commonly used species for extensive green roofs, *Sedum* spp. store water in their leaves. Geophytes have water-storing belowground organs. In the rainy seasons, they can put out shoots at once by utilizing stored carbohydrates, thus enabling them to flower and develop fruits within a very short period of time (Larcher, 2003).

- Small and curved leaf surface, erect and steep angle leaves

Under conditions of high radiation load and restriction of transpiration by stomatal closure, small leaves dissipate heat more efficiently than large ones (Gates 1968 and Grime, 2001). Also, effective reduction of water loss can be achieved by reduction of surface area and erect leaves (e.g. spherical cushion plants and many monocotyledons), leaves positioned in profile (e.g. *Iris* spp. and *Lactuca* spp.), curved surfaces (e.g. cylindrical leaves, scale-like leaves, needle and assimilatory shoot axes). Such leaves intercept incoming radiation at a steep angle thus avoiding strong radiation and overheating. Water conducting capacity is increased by enlarging the area of the conducting system and reducing the transport distance space (shorter internodes) (Larcher,2003).

- Evergreen

Many drought tolerant plants are evergreen. They have the advantage that they obviate the necessity to spend food resources on a wholly new photosynthetic apparatus each year (Billings and Mooney, 1968). It seems that older leaves act as winter food storage organs since lipids and proteins are mobilised and translocated from old to new leaves during the growing seasons. Evergreens can afford the apparent waste of these days of uncertain weather early in the growing season since their older leaves are already in photosynthetic operation (Grime, 2001).

3.1.3 Photosynthesis

The majority of plant species have C3 photosynthesis; 3-carbon compound is the first product in the PCA cycle (Photosynthetic carbon reduction cycle). To increase the efficiency of photosynthesis, additional metabolic systems have evolved in hot and dry or sometimes saline environments. They are C4 photosynthesis and CAM (Crassulacean Acid Metabolism) photosynthesis.

Many tropical grasses have C4 photosynthesis. They assimilate CO_2 into the 3-carbon carboxylic precursor phosphoenol pyruvic acid (PEP) to produce 4-carbon carboxylic acids as primary product. The initial fixation by PEP carboxylase acts as a CO_2 'concentrating' mechanism, therefore, C4 photosynthesis is superior to C3. The higher light compensation of C4 plants result in higher potential productivity. Also, C4 plants have higher nitrogen use efficiency because the amount of Rubisco, which can account for up to 30% of total leaf nitrogen in C3 plants, can be reduced by C4 photosynthesis. Stomatal conductance is smaller in C4 plants and it helps to conserve the water (Long, 1999). C4 plants have an advantage in high light, high temperature, and water and nutrient limited environment. Therefore, they could be very useful plants for extensive green roofs.

Many succulents including the family Crassulaceae have CAM photosynthesis. They can reduce the transpiration by showing net CO_2 uptake during the night and then, with closed stomata, fix it via the CAM photosynthetic pathway by day. Leaves of CAM plants are not structurally differentiated into tissues with different biochemistry, but CO_2 accumulation and RCR cycle assimilation are separated in time (Lawlor, 1993). Many of Sedum spp. are CAM plants and this is one of the reasons that they can survive well in the dry conditions where not many plants can. Durham et al. (2004) found that several species of Sedum survived and maintained active photosynthetic metabolism even after 4 months without water.

3.2 Modulative adaptation

Modulative adaptation is the mechanism that they can reduce the stress by switch photosynthesis, close of stomata and movement of leaves. This is readily resumed once the initial conditions are re-established.

3.2.1 Switch photosynthesis

Some CAM plants can shift from the C3 photosynthesis to CAM mode. For example, *Sedum acre* and *S. album* are C3-CAM plants and they switch from C3 photosynthesis metabolism to CAM in response to drought, salt stress or changes in the length of photosynthesis (Borland and Griffits, 1991). Certain species such as *Alloteropsis semialata* have the both photosynthesis of C4 and C3 (Larcher, 2003). Both of them achieve high carbon yields using C3 photysnthesis when they are in wet conditions and they follow CAM or C4 photosynthesis to reduce the stress in dry conditions. These shifts allow maximum exploitation of changing environments.

3.2.2 Closure of stomata

Stomatal closure is an adaptation to conserve water when plants are exposed to drought (Jevitt,1980). Stomatal closure increases the instantaneous WUE (water use efficiency) at the expense of absolute production (Jones, 1983). Therefore, there is little water loss or CO_2 assimilation during the long period of drought. According to Nagase (2003), it was shown that *Sedum kamtschaticum* var. *floriferum* 'Weihenstephaner Gold' showed low stomata conductivity when it was dry and high temperature, whereas the stomata conductivity became higher after a while of watering (Fig.2.5).

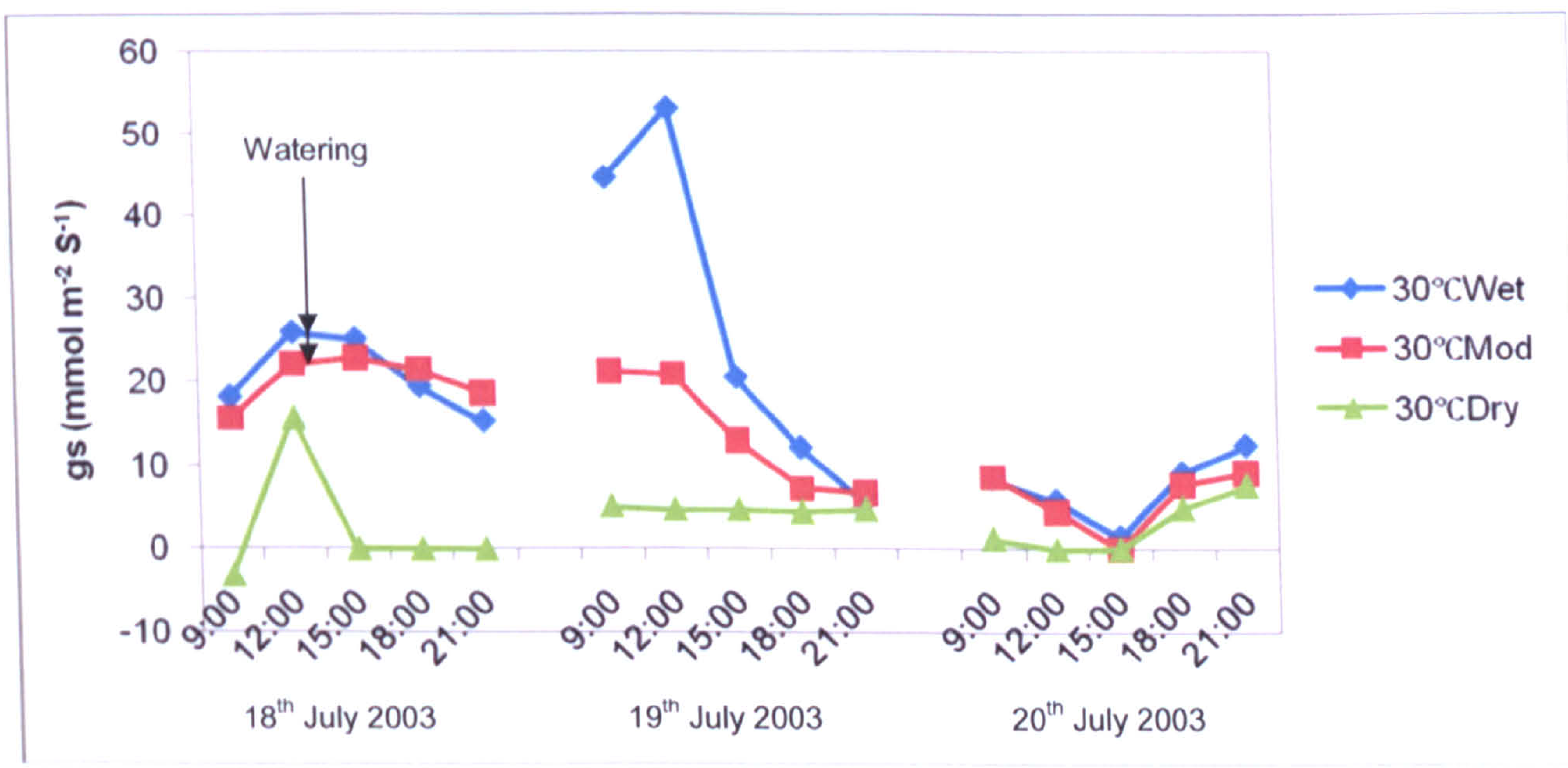


Fig.2. 5 The effect of watering on the mean stomata conductivity of *S. kamtschaticum var. floriferum* 'Weihenstephaner Gold' at 30°C over time

3.2.3 Movement of leaves

Paraheliotropic leaf movement, which is particularly well developed in legumes, protects water stressed plant leaves from damage by excess light, by heat and by the interactive effects of excess light and high leaf temperatures. When the leaves were restrained to a horizontal position, the degree of photoinhibitory damage increases with the time of exposure of light levels of solar radiation (Ludlow and Björkman, 1984). To reduce greatly intercepted irradiance, leaves can roll up (monocots), which is commonly observed in grass species or leaves can wilt, a response more commonly found in dicots (Farquhar et al.1989). If automatic irrigation systems are not available on green roofs, the observation of these leaf movements is important to judge the timing of irrigation. As soil moisture is consumed and not replaced, and tissue water stress cannot be corrected during the night, wilting will continue and intolerant species may eventually fall below the critical desiccation point and die (Hithcmough, 2004a).

Fig.2.6 Drought experiment of green roof plants in Emory Knoll farm in Maryland, US and some plants show leaf rolling after 8 days stopped watering.

3.3 Modificative adaptation

Modificative adaptation is morphogenic adjustment, including reduction of growth and these structural differentiations are usually irreversible. High dehydration tolerance is usually associated with slow rates of growth and decrease of CO_2 fixation by stomatal adjustment (Ludlow, 1980). In exposed environments, leaf areas tend to be smaller to reduce the water loss (Begg, 1980). These modificative adaptations help to withstand further exposure. In one study, the growth of two groups of *Agrostis stolonifera* formerly grown from populations found on two different sites, in exposed sea cliffs and in a standard green house, was compared on a windy rooftop in North Wales. The result showed that only the cliff population, which had small compact and tufted, with many short stolones, was damaged and continuous normal growth (Aston and Bradshaw,1966).

4. The potential habitats for plant selection for extensive green roofs

In this section, the potential plant habitats for extensive green roofs are explained. When plant species are chosen for green roofs, it is necessary to match their plant communities with environmental conditions in the built environment that mimic conditions in their original habitats (Lundholm, 2005).In fact, pioneer roof-greening researchers have tended to turn to their nearest dry habitats for inspiration and as source of plant species (Dunnett and Kingsbury, 2004a). Generally, these potential habitats share similar characteristics with extensive green roofs: open places where low vegetations grow, high wind exposure, high radiation, high temperature fluctuation, short season for favourable growth and shallow soils. However, it is worth noting that many of these plants from dry habitats tend to have deep roots and a high root/shoot ratio) but relatively poor stomatal control. Many plant spp. from SW USA such as *Penstemon* seem to have this biology. However, this does not work very well on an extensive green roof and it is important to choose plants with superior control of transpiration or other mechanisms. The potential habitats include alpine, sea coasts, warm semi-desert, Mediterranean regions (Dunnett and Kingsbury, 2004a) and urban wastelands. Their characteristics are explained as follows.

4.1 Alpine

An alpine environment can be defined as those physical and biological conditions occurring, on mountains, above the regional climatic upper limits of tree species (Billings, 1974). The opportunity for growth of alpine plants is limited to a short season because of the dominant environmental stress of low temperature. In addition, these areas are subjected to extreme cold coupled with the desiccation of dry wind and high radiation, especially in higher altitudes. Despite the prevalence of high rainfall in mountain areas, there is still a long dry period and the frequency of strong winds contributes to desiccation problems (Pardoe, 1995). During the growing season, biomass production is restricted not only by the cold temperatures, but also by desiccation and mineral nutrient stress because of low microbial activity (Grime, 2001). To adapt to these climates, the typical growth form of alpine plants is (1) Low stature or prostrate woody shrubs, (2) Graminoids such as grasses and sedges, mostly forming tussocks, (3) Herbaceous perennials often forming rosettes, and (4) Cushion plants of various types. This low growth allows them to retain an insulating covering of snow through the winter and reduces the impact of high levels of ultraviolet radiation (Pardoe, 1995). A feature of plants from high alpine areas is that they tend to live individually and they do not have the intense competition with which plants lower down have to contend. Further down the mountainside plants may live in the alpine meadows and they are able to stand more competition from grasses as well as other flowering plants (Bird and Kelly, 1998). Annual plants are uncommon in alpine environments because the short, cold growing season discourages a recurring reproductive cycle, while perennial plants have the advantage in that they do not need to reproduce annually and in their each year, they can put all their efforts into vegetative growth (Good and Millward, 2007). Many plants of rocky or alpine habitats are commonly grown on green roofs (Dunnett and Kingsbury, 2004a). Examples of alpine plants which are potential use for extensive green roofs are *Hieracium lanatum, Oenothera caespitosa,* and *Phlox douglasii.*

4.2 Sea coasts

There are several reasons why plants grow close to the sea. Some can tolerate, or even require, regular immersion in salt water at high tide and so grow where other plants cannot. Others get protection from frost (Phillips, 1987). However, generally, because of strong winds, salt-laden air and very free draining sandy soils, coastal environments are extremely taxing for plants (Dunnett and Kingsbury, 2004a). Although habitats near the sea are essentially watery, the presence of salt renders fresh water scarce, and the adaptations of seaside plants are frequently similar to those of plants in dry or desert like environments. The characteristics of the sea coast environment are (1) Rain that falls away rapidly through the sand, (2) Moisture is swiftly evaporated by the wind which is so prevalent on the sea coast. (3) Salt in the form of spray or seeping sea water reduces the osmotic absorption of water (Nellis, 1994). The drift line, the position just above the normal upper limit of the tide, is frequently associated with potentially fast growing annual plants such as *Galium aparine* and *Stellaria media,* which are familiar in a variety of other distributed habitats. The drift-line vegetation is subject to frequent disturbance at high tides and during storms, and colonising species grow and to produce seeds rapidly during the relatively short intervals between disturbances (Grime, 2001).

Plants which survive the severity of summer drought in maritime conditions are probably good candidates for green roofs. Moreover, costal plants would seem to fit well with roof design concerns which centre on cost- related factors such as heat island reduction, storm water runoff reduction and building energy efficiency because they are efficient water users, able to lower summer cooling costs and provide some ornamental value (Licht and Lundholm, 2006). The examples of sea coast plants for extensive green roofs are *Silene uniflora* and *Armeria maritima*.

4.3 Warm semi-desert

Warm semi-desert scrubs occur throughout the world in dry warm-temperate and subtropical climates (Whittaker, 1975). Semi-desert is distinguishable from true desert by its diffuse vegetation, although the ground is only covered to about 25%. In the frost-free subtropics and in the tropics the plant cover consists mainly of woody plants and succulents, and in the temperate zone with cold winters, mainly of half-shrubs, especially genus *Artemisia* (Walter, 1985). The typical semi-desert environment is characterized by having: (1) low, variable, and often unpredictable precipitation, (2) high air and soil surface frequently resulting in drought during hot months, (3) low relative humidity and extremely high potential evapotranspiration, (4) high solar irradiation, (5) steady to strong gusty winds (Gibson, 1996). In some cases, large areas of these habitats are dominated by one species, however, regions where changes in terrain and geology over relatively short distances create a complex of different habitats have particularly high potential, especially if these different habitats have a large proportion of endemic species (Dunnett and Kingsbury, 2004a). Shreve (1951) and Shreve and Wiggins (1964) recognized 25 life forms for the vascular plants in Sonoran Desert region. Within these life forms, the following would have potential for extensive green roofs: (1) Annual plants (2) Geophytes (3) Tussock grasses (4) Rosette plants with either succulent or non succulent leaves (5) Leafless stem succulents (Cactaceae) (6) Leaf succulents (7) Deciduous shrubs with soft wood (8) Evergreen shrubs.

4.4 Mediterranean regions

Mediterranean regions occur in five regions of the world: the Mediterranean Basin, California, central Chile, the Cape region in South Africa and south western and southern Australia (Vilá and Sardans, 1999). The climate of the Mediterranean is characterized by winter rain, sporadic frost and summer drought. In these areas, the most favoured time for plant growth is spring, when the soil is moist and temperatures are rising, or autumn, after first rain. In autumn, when rains recommence, the plants immediately take up production again (Walter,1985).

Two habitats may contain suitable species for extensive green roofs: Garrigue and grassland. A garrigue is open rocky ground characterised by many aromatic small shrubs, annuals, orchids and bulbs (Blamey and Grey-Wilson, 1993). Aromatic plants (e.g. *Thymus vulgaris*) are common in here to defence from browsing by goats (Brunie, 2000). Throughout the Mediterranean, grassy places and wayside contain many kinds of spring flowering spp. *Muscari* spp. (e.g. *Muscari armeniacum, M. comosum, M. neglectum*) and *Allium* spp. (e.g. *Allium roseum, A. neapolitanum, A. nigrum*) are common throughout, together with a vast range of herbaceous members of Leguminosae (Burnie, 2000). These species are potential use for extensive green roofs.

4.5 Urban wastelands

As well as exploring the environments of the world which were suggested above, it is very useful to look urban wastelands, which are unsown and unmanaged spontaneous vegetation. As previously mentioned, green roofs can be important places for habitats for biodiversity and locally characteristic plant communities are recommended for brown roofs. There are various types of urban wastelands: brick rubble, demolition sites, warehouse yards, industrial waste, railway sidings, vacant plots, abandoned allotments, walls, sites undergoing development (Gilbert, 1981). Urban soils are actually enriched with dirt and construction rubble (mainly cement, bricks and mortar), which leads to an increase in alkalinity (Sukopp, et al., 1979). In these areas, the conditions are often not uniform across a site, but are usually low in organic matter, reasonably fertile (though often lacking nitrogen) and rapidly draining (Wheater, 1999). In general, the higher species richness of cities compared with ecosystems in the countryside can be observed because of high habitat diversity of urban and industrial areas (Rebele, 1994). However, it is worth noting that the flora is not always occupied with native species in urban wasteland. During increasing disturbance of a particular vegetation structure, new species penetrate more easily than under stable conditions. River banks are for instance repeatedly disturbed by natural causes, where the periodically fluctuating water level and natural change in location of the bank continuously supply new areas, free of vegetation, for colonization (Sukopp, et al., 1979).

Caution must be applied in applying some species from wastelands because they may spread rapidly, especially grass spp. Green roofs are artificial environment and generally, there are many gaps when they are established. Some plants species gain a competitive advantage over other species by occupying a gap in a plant community that might otherwise remain unoccupied (Hitchmough, 1994c). It is better to choose stress tolerant species rather than species which develop too readily from seed and capacity for extensive lateral spread in wastelands.

Garden escapes which survive in urban wastelands may have potential for extensive green roofs. According to Gilbert (1989), the 'urban common' in Sheffield contains a particularly large number of colourful garden escapes which provide a succession of blooms from mid-June with *Tanacetum parthenium* and *Galega officinalis*, through summer with *Tanacetum vulgare*, until mid-October when the *Aster novi-belgii* finally die down after their 2 months flowering period.

Potential species for extensive green roofs can be found on old walls. In these areas, severe environmental constraints such as shortage of water, nutrients or light, or toxic substances are operating. In the UK, walls over 100 to 150 years old tend to be dominated by evergreen, stress-tolerant species which are long-lived. Examples are *Achillea millefolium*, *Cotoneaster* spp. *Hieracium* spp., *Sedum acre* and *Sagina procumbens* (Gilbert, 1981).

There is one study on how urban 'weed' species that grow in environments such as cracks in the sidewalk may be used in small modular planters on an exposed roof site in lower Manhattan, US. During hot, dry periods in the summer of 2005 the medium became totally desiccated and many plants died, however, some grew quite well. These included *Sedum* spp. and other succulents, but also a number of typical weeds, including *Euphorbia maculata*, *Cyperus esculentus*, *Veronica longifolia* and 2 moss species (Levandowsky, 2006).

5. Potential plant communities for extensive green roofs

Rather than looking at individual plant species, one can also consider whole plant communities as having potential for green roof use. One of the advantages of dealing with communities is that species that occur naturally together in a given plant community probably tolerate broadly similar conditions, and have similar management requirements (Hitchmough, 2004d). As has previously been mentioned, in many cases plant communities can be readily established from seed mixtures sold by companies engaged in ecological restoration or the marketing of wildflowers (Dunnett and Kingsbury, 2004a). The potential plant communities for extensive green roofs include North American Short Prairies, Central European Steppe, and Limestone vegetation (Dunnett, personal communication).

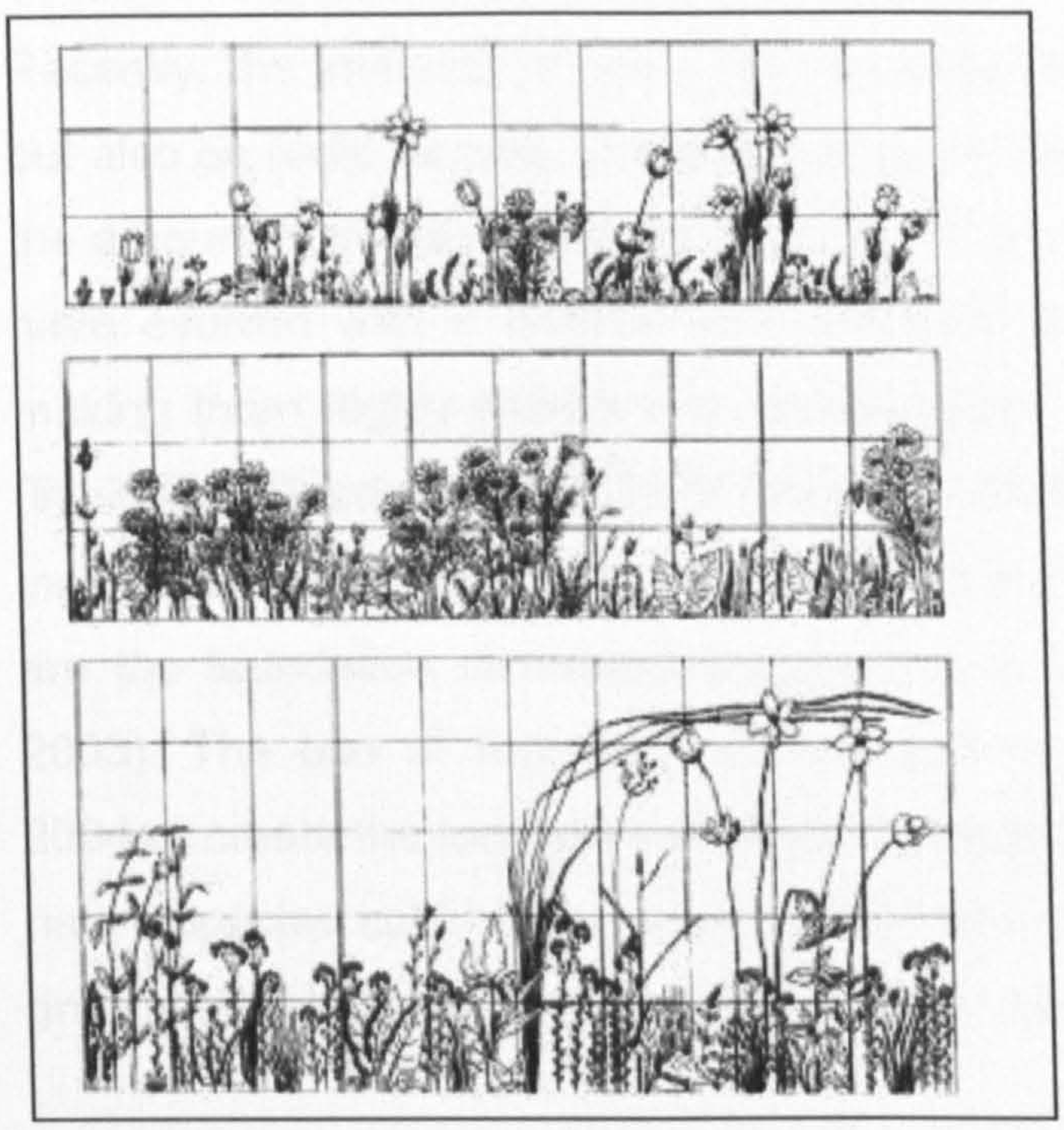
5.1 North American Prairies

Prairie vegetation is naturally restricted to North America, where it stretches from the east of the Rocky Mountains to the Appalachians (Hitchmough, 2004d). Typically, prairies can be found in areas that receive insufficient rainfall to support fully developed forest, but enough rainfall to support a closed perennial herbaceous layer with little bare soil visible (Coupland, 1979). Because of the cold winter and the drought of late summer, the growing season is limited to only about 4 months in spring and early summer (Walter, 1985). Several thousand species of vascular plants, including close to 300 grasses, bloom in the prairie regions and wildflower displays and abundance of wild fruits vary from year to year, depending on moisture and sunlight (Jones and Cushman, 2004). Whist prairie is very rich in perennial forbs, it is typically dominated by warm season grasses, which have C4 photosynthesis (Hitchmough, 2004d).

The region can be divided into three by grass species: tall grass, short grass and mixed grass. For green roofs, short grass prairies may be suitable. Dry limestone prairie and sandstone bluff prairie (occurs locally on SW-facing slopes of loses bluffs along glaciofluvial outwash along the Illinois and Sangamon rivers) are examples of short grass prairies (Hoffman, 2002). In short grass prairies, $CaCO_3$ nodules are found at a depth of only 25cm, the humus horizon is very shallow, therefore, the plants roots are shorter (Walter, 1984). As an adaptation to aridity, shortgrasses such as buffalo grass produce unusually thick mats of roots near the soil surface (Bolen, 1998). Short grass prairie tends to be dominated by *Bouteloua gracilis* and *Buchloe dactyloides* (Joern and Keeler, 1995). During the winter, the areas which are dominated by short grasses appears drab and lifeless, however, if the spring rains come on time and when with enough frequency, the short grass plains transform into lush green meadows carpeted with wildflowers. In rocky places, it is carpeted with cushion and mat plants similar to those that grow in the alpine regions (Jones and Cushman, 2004).

5.2 Central European Steppe

The Eurasian steppe derives from the Russian name of one of the commonest genera, Stipa (Joyce and Wade, 1999). Steppe is the term used to describe a diverse range of dry grasslands, which typically experience extremely cold winters, moist springs and hot dry summers. Because of this, most steppe species grow and flower between mid-spring and early summer, then enter a dormant state (Hitchmough, 2004c).In the same way as North American Prairies, only about 4 months of favourable growth season in spring and early summer occur in Central European Steppe. Zonal steppe vegetation is dominated by the turf-formation grasses, such as *Stipa, Festuca, Koeleria, Poa* and *Carex* spp. Typical plant species, which develop in spring, are *Tulipa, Iris, Gagea, Adonis* spp. and some species of *Astragalus* (Chibiloyov, 2002). In addition, winter annuals such *as Draba verna, Holosteum umbellatum* are abundant. Other herbs make their appearance in summer (*Salvia nutans, S. nemorosa, Serratula spp., Jurinea spp., Phlomis spp.,* etc.) (Walter, 1968). The steppe tends to be associated with low-fertility and low-productivity conditions, however, East European steppe is very different. They show the colourful blossoms, and only in autumn do they give the impression of dryness. The example of the vertical projection of meadow-steppe in spring in Pokrovskaja Russia is shown in Fig.2.7 (Walter, 1968). The plants in this figure are also potential for use in extensive green roofs.



Top: Beginning of April
Pulsatilla patens
Carex humilis

Middle: End of April
Adonis vernalis
Hyacinthus leucophaeus

Bottom: End of May
Myosotis sylvatica
Anemone sylvestris
Senecio campestris
Stipa spp.

Fig.2.7 Vertical projection of meadow-steppe in spring in Pokrovskaja Russia (Walter, 1968)

5.3 Limestone vegetation

A calcareous grassland, which has a high lime content of the soil, is particularly rich in species (Ellenberg, 1998). This is because in many cases, high plant diversity is often related to the fact that limestone derived soils are not very fertile, as a result, highly vigorous dominant species are absent or checked, allowing more species to co-exist (Hitchmough, 2004c). Calcareous soils are usually permeable to water and therefore warmer and drier, and they contain great amounts of Ca^{2+} and HCO^{3-}, therefore, pH is higher than other soils. Nitrogen is more rapidly mineralized in calcareous soils and P, Fe, Mn and most heavy metals are less available than in acid soils (Larcher, 2003). Limestone vegetations bear some resemblances to extensive green roofs: (1) Frequently dry and well aerated but sometimes moist and water logged, (2) Low-fertility thin soils are often encountered, (3) All climatic and altitudinal situations may be encountered (Jeffrey, 1987). Typical European limestone flora consists of a low turf dominated by dense tussock grasses, such as *Festuca* spp., along with a wide range of assemblage of colourful wildflowers, such as *Campanula rotundifolia, Thymus vulgaris*, and *Euphorbia cyparissias*. The short stature, visual appeal, and drought tolerance of this vegetation is a perfect model for roof greening (Dunnett and Kingsbury, 2004a).

6. Native species for extensive green roofs

Recently, the interests of using native plants have increased not only at ground level but also on roofs as well. Using native plants has a lot of benefits such as reduction of the amount of irrigation, reducing the use of pesticides and maintenance because they have evolved with a diverse environmental ecological challenges over a long time making them highly resistant to damage from climate, disease, insects and animals (White and Snodgrass, 2003). In addition, native plants coevolved with microbes, fungi, insects and animals to from a complex network of survival relationships. Native plants are the foundation of natural ecosystems of the food chain (White and Snodgrass, 2003). The use of regionally native replaces lost habitat (Dunnett and Kingsbury, 2004a), create the local distinction and provide the educational value. In addition, using native species could be required for planning permission in sensitive location such as green belt for nature conservation (Dunnett, personal communication).

However, as it was mentioned in chapter 1 (3.2 North America) many native plants also have evolved in deep soils of a particular structure and microbial and nutrient balance, and sometimes native plants are not able to adapt to green roof culture, because this is such an extreme environment (White and Snodgrass, 2003). Especially the UK climate is relatively mild, the native species, which can stand on the roof environment, might be found only in the limited areas. There may be much more potential non-native species from suitable habitats than there are suitable native species (Dunnett, personal communications). Some non-native plants can provide attractive flowers and foliage over the whole growing season, therefore, the use of non native species can give considerable benefit where aesthetic consideration are important. Some non-native plants have wildlife value, for example, *Verbena bonariensis* have a valuable nectar source for butterflies over a very long season (Dunnett and Kingsbury, 2004b). It may be possible to maximize their benefits to mix native and non-native plants.

7 Functional criteria for plant selection for extensive green roofs

As discussed above, plant survivability is the most important for plant selection for extensive green roofs. However, only considering plant survivability may result in using same kinds of plant species for extensive green roofs. As well as survivability, functional and aesthetic criteria should be taken into account (Hitchmough, 1994d).

One of the functional criteria of plant selection for extensive green roofs is whether the plant selection and community are suitable for the aimed function. Nowadays, green roofs tend to be installed to achieve some environmental benefits such as creating habitats for biodiversity. As was mentioned in chapter 1 (4.3 Maximizing green roof benefits), some studies have shown that different green roof vegetation types influence green roof performances differently. Therefore, it is necessary to make sure that the used vegetation is likely to achieve the aimed function effectively rather than just covering the roof by vegetation.

8. Aesthetic criteria for plant selection for extensive green roofs

The appearance of green roofs changes over time, therefore, aesthetics should be considered throughout the year to create seasonal interest. Many plant species flower in spring to early summer, however, combining early and late flowering species may enable to extension of the overall flowering season. Using evergreen species and grasses makes seasonal interest in winter. A mix of hardy succulents, herbaceous perennials, and annuals may be combined to achieve year-round interest (Snodgrass and Snodgrass, 2006). Phenology related with visual aesthetics will be explained in detail in Chapter 5.

Accessibility and visibility are one of the key factors to decide the characteristics of planting. The more visible and accessible the roof, the better it is better to have more aesthetic design and seasonal interest. If it is not visible and accessible, simple sedum/moss communities or dry meadow would be acceptable (Dunnett and Kingsbury, 2004a).

9. Potential plant group

Taking account of the mechanisms to enable plants to adapt to dry environments, potential habitats and plant communities, functional and aesthetic criteria, the main potential plant groups for extensive green roofs are bulbs, annuals, herbaceous perennials and grasses. Herbaceous perennials and grasses and sedges are the main research focus for plant selection research at present (e.g. Bovin et al. 2001, Dunnett and Nolan, 2004 and Moran et al.,2003), and there are several research projects related to Sedum species. There is little research about annuals (Kircher, 2004), and very little research published in English language for bulbs. However, bulbs and annuals have huge potential because of their characteristics of adapting the dry environment which is the key factor of growing plants on the roof. The natural habitat, adaptation, suitable features and plant examples are summarized as below. The detail and their experiment of their performance will be explained in later chapters.

Table 2.3 Plant groups for green roofs (Adapted from Kingsbury, 1996, White and Sondgrass,2003, Dunnett and Kingsbury, 2004a, Snodgrass and Snodgrass, 2006)

	Annuals	Bulbs	Grasses	Hardy succulents	Herbaceous perennials
Adaptation to the green roof environment	Avoiding the most harsh time of the year as dormant seed, and germinating, growing and flowering in more benign periods	Growing and flowering early in the year and die back underground to survive baking summer temperatures.	Morphology C4 photosynthesis They are able to colonize the open to the sun and do not need much water and nutrient.	Morphology CAM photosynthesis	Morphology
Suitable features	Self-seeding	Short bulbs	Short grass Not too much self-seeding	Evergreen and or coloured and textured foliage	Evergreen and or coloured and textured foliage
Advantage	Quick establishment Flowering is rapid Bright flower colour Long flowering	Early flowering Quick establishment Little supplemental watering is required	Add motion and texture, and more vertical structure Suitable for naturalistic meadow-like planting and more formally as accent plants Winter interest	Very drought tolerance Winter interest	Variety of colour, texture and seasonal interest
Example	*Eschscholzia* *Gypsophila* *Linaria* *Linum* *Tripleurospermum*	*Allium* *Crocus* *Iris* *Muscari* *Tulipa*	*Festuca* *Melica* *Stipa*	*Delosperma* *Sedum* *Sempervivum*	*Achillea* *Dianthus* *Gypsophila* *Thymus* *Alyssum* *Campanula* *Potentilla* *Anthemis* *Aster* *Soildago* *Centaurea*

10. Previous research for plant selection for extensive green roofs

In this section, previous research, which is related to plant selection for extensive green roofs, is summarized. The main previous studies of plant selection for extensive green roofs could be divided into three: (1) Performance of herbaceous perennials, succulents, grass, herbs, annuals under the different watering regime and/or soil depth in fields or on roofs, (2) Long term spontaneous vegetation change research on extensive green roofs, (3) Plant physiological research. (4) Suggestions from the experience of green roof instalment are also useful information. However, in general, there are still many research gaps for plant selections for extensive green roofs and the research has not yet reached the stage where it is possible to convince landscape architects which species can be used in the certain environments, at different substrate depths and levels of supplementary irrigation of green roofs. Details of each study can be explained as follows.

10.1 Performance of herbaceous perennials, succulents, grasses, herbs, annuals under the different watering regime and/or soil depth in fields or on roofs.

This category is the most commonly studied subject for plant selection for green roofs because the depth of substrate and irrigation tend to be limited, especially for existing building. The depth of substrate and microclimate, the ability to withstand summer drought will be the main factor deciding plant choice, whereas in regions with prolonged severe winters, cold hardiness will play a pivotal role (Dunnett and Kingsbury, 2004a).

The earliest plant selection study for extensive green roofs, published in English, concerns the effect of substrate depth on freezing injury of six herbaceous perennials (*Ajuga reptans, Arenaria verna* 'Aurea', *Armenia maritima, Draba aizoides, Gypsophila repens, Sedum x hybridum*) in Québec, Canada (Bovin et al, 2001). The different species have different winter hardiness, *S. x hybridum* was more damaged at 5cm soil depth than 10 cm and 15 cm in two winters, and *A. reptans* and *G. repens* were more damaged at 5 cm soil depth than the other two depths in one winter.

There are several studies of hardy succulents and native species in North America. For example, eighteen Michigan native plants (*Agastache foeniculum, Allium cernuum, Aster laevis, Coreopsis lanceolata, Fragaria virginiana, Juncus effusus, Koeleria macrantha, Liatris aspera, Monarda fistulosa, Monarda punctata, Opuntia humifusa, Petalostemon purpureum, Potentilla anserina, Rudbeckia hirta, Schizachyrium scoparium, Solidago rigida, Sporobolus heterolepis* and *Tradescantia ohiensis)* were evaluated over three years for growth, survival during both establishment and overwintering, and visual appearance in Michigan, USA. For unirrigated 10 cm depth of substrate on extensive green roofs, the plant survival was limited; *A. cernuum, C .lanceolata, O. humifusa* and *T. ohiensis* were suitable. If irrigation was available, other native species were more successful (Monterusso, et al., 2005). In another study in Michigan, 25 Crassulacean species (*Graptopetalum paraguayense, Phedimus* *spurius* 'Leningrad White', *Rhodiola pachyclada, R. trollii, Sedum acre, S. album* 'Bella d'Inverno', *S. clavatum, S. confusum* minor form, *S. dasyphyllum* 'Burnati', *S. dasyphyllum* 'Lilac Mound', *S. diffusum, S. hispanicum* diploid, *S. kamtschaticum, S. mexicanum, S. middendorffianum, S. moranense, S. pachyphyllum, S. reflexum, S. sediforme, S.* 'Rockery Challenger', *S.* 'Spiral Staircase', *S. spurium* 'Summer Glory', *S. surculosum* var. *luteum, S.* x *luteoviride, S.* x *rubrotinctum*) were grown on roof platforms at substrate depths of 2.5, 5.0 and 7.5cm in the filed over three years. By the end of year three, only 6, 8, and 8 taxa of the original 25 taxa were still present respectively. These species were *P. spurius* 'Leningrad White', *S. acre, S. album* 'Bella d'Lnverno', *S. hispanicum diploid, S. kamtschaticum, S. middendorffianum, S. reflexum* and *S. spurium* 'Summer Glory'. Plant diversity and absolute cover in the 2.5cm depth plots was lower than at the 5.0cm and 7.5cm plots (Rowe, et al. 2006, Durham, et al., 2007).

A variety of plants from subalpine, upland, costal barren and wetlands were examined in roof filed trials in Medford, MA, USA. *Danthonia spicata, Juncus tenuis, Carex scoparia, Distichlis spicata, Spartina patens, Chrysopis mariana, Coreopsis rosea, Aster spectabilis, Oenothera fremontii, Salvia nemorosa, Solidago sphacelata* 'Golden Fleece', *Sedum ternatum, Sedum sexangulare, Sedum spurium* 'John Creech', *Carex pennsylvanicum, Arctostaphylos uva-ursi, Epimedium perralderianum* 'Frohnleiten', *Fragaria* x 'Lipstick' were grown at the depth of 12.7 cm. In full sun trials, *D. spicata, C. rosea, S. ternatum, S. sexangulare, Sedum spurium* 'John Creech' were found to survive well during an extended period of non-irrigation. After nearly a year of observation, they continue to perform well (Licht and Lundholm, 2006).

In the UK, plant selection study has been carried out in Sheffield since 2001. Dunnett (2004a) studied a range of different drought tolerant plants (*Armenia maritima* 'Alba', *Artemisia schmidtiana* 'Nana', *Calamintha nepeta, Dianthus deltoides, Eryngium bourgatii, Festuca glauca, Festuca scoparia, Gaura lindheimeri, Gypsophila repens* 'Alba', *Kniphofia* 'Border ballet', *Limonium platyphyllum, Nepeta racemosa* 'Walker's low', *Nepeta* × *faassenii, Origanum laevigatum* 'Herrenhausen', *Salvia* × *sylvestris* 'Blue Queen', *Sedum acre, Rhodiola rosea, Stachys byzantina, Veronica spicata* 'Nana') in a substrate depth of 10 cm or 20 cm, with or without limited supplementary irrigation on the roof. He concluded that the main limit to plant growth was water availability rather than the depth of substrate on its own. In the initial two years of the experiment, it appeared that low-growing species and typical extensive green roof taxa, such as *S. acre* and *D. deltoides* were advantaged at the lower substrate depth. This seemed to be a result of their competitive displacement by more vigorous species at the greater substrate depth, whereas at 10 cm competitive vigour of those more bulky taxa was constrained. However, over the long-term this advantage at the lower substrate depth appears to be lost. Indeed, these taxa exhibited sharp declines in abundance at 10 cm compared to their survival at the greater substrate depth. The results indicate the dynamic nature of green roof systems, particularly in their early establishment phase, and highlight the need for long-term monitoring of plant performance to avoid misleading early conclusions (Dunnett and Nagase, 2007).

Kircher (2004) studied the effect of adding annuals, or cuttings of several sedum-species to five seed-mixture on extensive green roofs after first and second year after sowing in Bernburg, Germany. In addition, two different fertilising varieties were tested. Only on fertilized plots in the second year a covering rate of over 60% was reached. The influence of fertilizer in the second year was substantially larger than the effect of the seed-mixtures. Suitable annual plant species were *Gypsophila elegans, Iberis amara, Silene armeria* and *Xeranthemum annuum,* which were able to form aspects in the first year. *G. elegans* showed stable populations in the second year too. The trial confirms the importance of fertilisation on shallow-substrate roof-gardens. Branches of *Sedum album*, *S. sexangulare* and *S. reflexum* can reach high covering relatively fast, but on larger areas clearly cause higher costs. Even a relatively low addition of 10 g/m² in seed-mixes can result in a significant effect and reduce the proportion of grasses, if fertilised even in the first vegetation period after sowing.

10.2 Long term spontaneous vegetation change research

Understanding spontaneous vegetation change would be important for plant selection since they describe which species are likely to survive in a long time on a roof environment. It also helps understanding which factors affect plant survival on green roofs.

Koehler (2004b) has been researching vegetation dynamics of several green roofs in Germany for more than 20 years. Paul Lincke Ufer in Kreuzberg (established in 1984, 10 different slopes and exposure, studied since 1984) and UFA fabrik in Berlin (established between 1984 and 1996, 6 different roofs, studied since 1998) are examples. The roof of Paul Lincke Ufer was covered with turf vegetation mat and after some years, *Allium schoenoprasum* became the dominant plant cover with more than 75%. The emergent plants are different between years probably because of climate and disturbance and total number of plants on these roofs are declining. In UFA fabrik, some of green roofs were established in 1985 and the seeds from a wide range of meadows and grasslands of Europe including the Alps were sown. The irrigation in the first year resulted in a higher frequency of plant species, however, only a few of the non-typical plants of the region of Central Europe could survive. After some years, Sedum reached nearly 60% of the complete vegetation stand (Koehler, 2003). Koehler (2003, 2004b) summarized that the available water affected the diversity of plant competition. In addition, the depth of substrate, the storage capacity of substrate, building condition such as exposure and slope and annual maintenance are the important factors.

10.3 Plant physiological research

Studying in detail plant performance in controlled environments such as in a green house provides important findings for plant physiology, particularly for drought tolerance on extensive green roofs.

In plant physiological studies, there are several studies to indicate the drought tolerance of Sedum spp. Van Woert, et al. (2005) investigated the relationship between watering and substrate depth using Sedum spp. mixture (*S. acre, S. album, S, kamtschaticum* var. *ellacombianum, S. pulchellum, S. reflexum, S. spurium* 'Coccineum', *S. spurium* 'Summer Glory') in a green house. It was shown that over the 88 day study, water was required at least once every 14 days to support growth in green roof substrate with a 2 cm media depth. However, substrates with a 6 cm media depth could do so with a watering only once every 28 days. Although vegetation was still viable after 88 days of drought, water should be applied at least once every 28 days for typical green roof substrates and more frequently for shallower substrates to sustain growth. In another study, the growth of four sedum species and cultivars (*S. kamtschaticum* var. *floriferum* 'Weihenstephaner Gold', *S. rubrotinctum, S. rupestre*, and *S. spathulifolium* var. *purpureum*) were investigated under the combination of three constant temperatures (14°C, 22°C, 30°C) and three watering regimes (wet, moderate, dry) in 5cm substrate in a green house. All four species produced their greatest biomass at 14°C in the wet regime, whereas growth was restricted at 30°C in the dry regime. However, drought tolerance and growth rate varied among species. Growth of S. *kamtschaticum var. floriferum* 'Weihenstephaner Gold' was better in the wet regime at 30 °C than the other species. It may be that they could grow slowly at higher temperatures if they were watered. *S. rubrotinctum* showed the best growth under the dry regime at any temperature. Growth of *S. rupestre* was restricted in the dry regime at 22°C and in any watering regime at 30°C. For *S. spathulifolium* var. *purpureum,* the growths were always lower than other species, and even at 22 °C in wet regime, they showed a little growth (Nagase and Thuring, 2006).

Nagase and Thuring (2006) showed that the timing of drought affected plant performance. Five species (*Sedum album, S. sexangulare, Delosperma nubigenum, Petrorhagia saxifraga* and *Dianthus deltoides*) were tested for their response to the drought conditions (early, late and no drought) when grown in 3 depths (3, 6 and 12 cm) of two substrates (expanded clay and expanded shale). The result showed that most of species had produced less shoot biomass after early, rather than late, drought. While the Sedums performed well in all depths, plants grown in 6 cm and 12 cm substrate produced significantly more shoot biomass than those in 3 cm. *Sedum album and S. sexangulare* performed well under most conditions, although S. *sexangulare* was stunted by early drought. *D. nubigenum,* although succulent, only performed consistently when provided with water. When subjected to drought, the herbaceous taxa (*P. saxifraga* and *D. deltoides*) always had fewer survivors in the expanded shale.

10.4 Suggestions from experience

Hauth and Liptan (2003) recorded plant information based on visual observation of plant species that have survived initial establishment and 3-7 years of sustained growth on green roofs (substrate depth 7.5cm and 11.5cm, and with supplementary irrigation) in Portland Oregon. Successful plants were 11 species of Sedums (*S. acre, S. album, S. divergens, S. hispanicum* var. *minus, S. kamtschaticum* var.. *ellacombianum, S. oreganum, S. rupestre erectum, S. sexangulare, S. spathulifolium, S. spurium* 'Dragon's blood', *S. telephium*) and following species : *Sempervivum tectorum, Delosperma cooperii, Delosperma nubigenum, Achillea tomentosa, Cerastium tomentosum, Festuca glauca, Gilia capitata, Lupinus bicolour, Nierembergia, Potentilla neumanniana, Thymus vulgaris, Thymus serpyllum, Teucrium cossonii majoricum, Teucrium chamaedrys, Polypodium glycyrrhiza, Muscari* and *Camassia quamash.*

Snodgrass owns the nursery which specialized for green roofs and provides useful information from his experience. White and Snodgrass (2003) summarized the plant selection criteria for extensive green roofs as follows; Low-growing, shallow-rooted, perennial plants that are heat, sun, wind, drought, salt, disease and insect tolerant are preferred for extensive green roofs. Plant species should be ecologically compatible, fast growing but not invasive, flame retardant and have low nutrition requirements. They should have shallow, fibrous roots, long life expectancy or be self-propagating, lightweight at maturity and have low maintenance requirements, low-growing ground covers resist drying out and being blown over by wind. Evergreen plants and seasonally flowering plant make good combinations for providing aesthetical pleasing extensive green roofs year-round. In supplying first 100 extensive green roofs, Snodgrass (2005) showed that there are six main lessons which they learned. The first is to separate plant usage into two categories: ground covers and accents. Ground cover characteristics should be plants that can spread from a plug to 25-30 cm within a year, be persistent year round, have a fibrous root structure to hold the media together, and be able to live for the life of the roof. Accents, on the other hand, may be seasonal, are not required to be stabilizers for the media, should act as contrasts to the groundcover and provide overall visual interest. The second is that, generally speaking, the most reliable kinds of green roof plants are hardy succulents. This seems to be the case across many regions of the country with some variability due to local climates. Third, unlike northern Europe, in the United States there are not only significant overall regional climatic differences, but there are also myriad microclimates that exist and affect installations. Fourth, there is considerable market pressure to have regionally appropriate natives utilized in the installations. Fifth, upfront maintenance is a worthwhile investment to ensure the long term health of the green roof.

10.5 Summary of previous research for plant selection for extensive green roofs

Overall, there are a few plant selection studies for extensive green roofs and the number of tried-and-test plant species also has been limited. Moreover, most of previously investigated plant species are sedum or herbaceous perennials and grasses or spontaneously colonized flora. As it was introduced in 9. Potential plant group, not only Sedum, herbaceous perennials and grasses, but also, other plant groups such as annual plants and bulbs are likely to be tolerant for green roof environment and it is worth to study their performance on the roofs. There are also few studies to show which plant communities are possible growing in shallow green roof substrates with limited irrigation and requiring low maintenance. It is necessary to investigate not only drought tolerance of individual plant but also the performance of vegetations including establishment and plant competition. Probably, other important works are investigation of the long-term dynamics of green roof systems including flowering and weeds invasion. This study is essential to create aesthetic green roofs for amenity places although current studies tend to focus only survivability. In addition, it is interesting to investigation of the comparison between the various types of plants and vegetations to achieve different environmental benefits. There has been little consideration of whether green roof vegetations confer equally environmental benefits, for example, in terms of stormwater runoff reduction. Following experiment chapters are aimed to fill these identified research gaps.

Chapter 3 Plant performance on the roof

3-1 Seedling emergence of potential plants for extensive green roofs in the UK: Effect of sowing season

Abstract

Plant meadows established by direct sowing of seed mixtures have potential for extensive green roofs since they are cost effective, require low maintenance and are easy to install for large areas. However, there has been limited research of seed germination for extensive green roofs and it may be one of the reasons that direct sowing is not widely used. This study investigated the establishment from seeds of 62 perennial plant species that may be suitable for extensive green roofs in the UK. The purpose of the study was to select the species with good levels of germination in the field and to determine appropriate sowing season (spring and autumn). 10 seeds for each species were sown in 9 cm pots with appropriate watering in the spring and in the autumn and arranged randomly in a block on an experimental green roof. The results showed a wide range of germination rates by species (0%-96.7%) and 30 species had more than 50% of germination rate in the spring sowing. 18 species which had germination rates below 30% in the spring were sown again in the autumn to detect their chilling requirement. However, most of these species still had low germination rate after chilling. Therefore, spring might be the best season for direct sowing of seeds on roofs to get the quickest establishment. The species with high germination rates included *Allium schoenoprasum*, *Nepeta x faassenii*, *Linum perenne*, *Melica ciliata*, *Saponaria ocymoides*, *Anacyclus pyrethrum* var. *depressus*, and *Dianthus carthusianorum*. On the other hand, the species with the poorest germination rates, included *Jasione montana*, *Ajuga genevensis*, *Hieracium alpinum*, and *Primula veris*. Various percentages were observed in grassland and meadow species. Between the forbs, there was a positive relationship between germination rate and the size of seeds such that bigger seeds showed higher germination rates than smaller seeds.

1. Introduction

1.1 Direct seed sowing for green roofs

Plants occurring naturally in self sustaining, low maintenance meadows can be established by the direct sowing of seed mixtures. Meadows which are established by direct sowing may have potential for extensive green roofs since they are cost effective, require low maintenance and are easy to install. These are important factors for wider use of green roofs. However, this technique is not widely used for extensive green roofs and at the time of writing no wholly seeded green roof installations exist in North America (Snodgrass and Snodgrass, 2006). This may because of their disadvantages; generally two or three years for coverage and development are required, as well as irrigation during the germination and establishment phases (Snodgrass and Snodgrass, 2006). Also, the stronger growing species may eliminate weaker growing species in complex seed mixtures, especially if one is more sensitive to climatic conditions than the other (Dunnett and Kingsbury, 2004a). As a result, more reliable plant material, in the form of plugs or pots, is preferred to seed mixtures in spite of their greater expense. Perennial seed mixtures could be combined with plug plants, annuals, or bulbs but further research is required to study the competition effects between these combinations in the green roof environment. In Switzerland, seed mixes are relatively common for green roofs which are aimed to enhance biodiversity since meadows create appropriate habit for insects and birds and certain seed mixtures for extensive green roofs are available. These mixtures are formulated according to geography and microclimate, and include mix names like Basel mix and Zurich mix. In the UK, a seed mixture including *Leucanthemum vulgare*, *Primula veris*, *Anthyllis vulneraria*, *Malva moschata*, and *Daucus carota* was used with grass mats for CUE (Centre for Understanding the Environment) building in London (Greenroofs.com, 2006).

1.2 Composition of a seed mixture

While information detailing seed mixtures for extensive green roofs is limited, some aspects of wildflower seeding at ground-level could be applied. The composition of a seed mixture usually compromises a blend of what is desired and what is possible in terms of cost, germination and availability (Bayfield, 2004). In the case of green roofs, accessibility and visibility should also be considered. Grass mixtures may be appropriate for inaccessible and non-visible areas, while a higher ratio of colourful flowering forbs would be desirable for visible amenity spaces. Generally, wildflower seeds are sown in combination with grasses which germinate quickly and establish a fibrous root system that helps stabilise the soil (Bayfield, 2004). The general criteria for species selection in wildflower mixes that could be applied for extensive green roofs is summarized as below (Department of Transport, 1993; Kingsbury, 1996).

Fundamental

- Ecologically suitable for existing soil/ water conditions (considering the typically infertile substrates and dry conditions on extensive green roofs)
- Commercially available and cost effective

Establishment

- Seeds which germinate easily over a range of temperature conditions, preferably without dormancy mechanisms

Survivability

- Predominantly long-lived species
- Not highly competitive or invasive (e.g. *Arrhenatherum elatius, Holocus lanatus, Holocus mollis, Lolium perenne*)

Performance

- Colourful flowers
- Long flowering period (phenology of individual species)
- Attractive to insects as food and nectar sources

Dry meadows can be established on green roofs from readily available wildflower and grass seed mixtures, provided that the substrate is more than 5 cm deep (Dunnett and Kingsbury, 2004a). Industry standards for these mixes on the ground dictate a ratio of 20 % wildflowers to 80 % grasses (Scott, 2004, Luscombe and Scott, 2004). However, this ratio of grass may be too high for extensive green roofs since the grass may out-compete wildflowers (English Nature, 2006). Table 3.1.1 shows a meadow-like seed mix for German extensive green roofs, designed for 15 cm substrate sown to 5g/ m^2 (Kolb and Schwarz, 1999).

Table 3.1.1 Perennial seed mix for German extensive green roofs (Kolb and Schwarz, 1999)

Forbs	Per cent by weight
Achillea millefolium	2
Allium schoenoprasum	4
Anthemis tinctoria	6
Campanula rotundifolia	2
Dianthus carthusianorum	6
Dianthus deltoides	6
Geranium robertianum	4
Leucanthemum vulgare	4
Petrorhagia saxifraga	4
Pilosella officinarum	3
Plantago lanceolata	4
Potentilla argentea	2
Prunella grandiflora	5
Ranunculus bulbosus	6
Sanguisorba minor	5
Thymus pulegioides	3
Thymus serpyllum	3
Forbs total	69%
Grass	
Anthoxanthum odoratum	2
Briza media	7
Festuca ovina	10
Poa compressa	2
Sesleria albicans	10
Grasses total	31%

1.3 Sowing season and dormancy

Knowing the best season for sowing a perennial seed mixture is a key to successful establishment. According to Bayfield (2004), late summer sowing (August – September) provide the best results, with spring (April – May) next best for wildflowers. Spring sowing has the benefit of a full season's growth whereas autumn sowing allows young plants to become well-established over winter and vigorous growth the following spring.

Dormancy should be considered when selecting species for seed mix. Dormancy occurs when the seed is capable of germination but fails to do so because the appropriate conditions are absent (Hitchmough, 2004d). The dormancy needs of herbaceous species will determine a spring or autumn sowing (Bayfiled, 2004).For example, the seed of species whose native habitat drop below freezing in winter do not germinate until they have spent some time fully moistened at low temperatures, generally in the range 1 - 10°C (Bewley and Black, 1994). This mechanism prevents germination in autumn, protecting young seedlings from exposure to cold climate winters (Handreck and Black, 1994). Dormant seeds may survive for a long periods in the soil seed bank, with intermittent germination of a part of the population. This dormancy must be relieved when there is a good chance of successful seedling establishment (Murdoch and Ellis, 2000). Certain dormancy patterns or extremely slow germination rates by some species render them unsuitable for seed mixtures. For example, *Primula veris* and *Pulsatilla vulgaris* have deeply dormant seeds, they may require more than 6 months of chilling and *Euphorbia* and *Geranium* species tend to have erratic germination rates (Hitchmough, 2004d).

1.4 Amount of seed requirement

Seed number per gram (i.e. seed size) and germination rate should be always considered when developing a seed mixture. Mixes with large quantities of fine seeded species which have good germination and rapid establishment will be dominated by these species. Moreover, competitive species with low seed numbers may be more successful than poor establishers in high seed numbers (Luscombe and Scott, 2004). Total amount of seed requirement can be calculated with the following formula. Firstly gram seed requirement per m^2 must be calculated and multiplied by total area (Hitchmough, 2004d). Number of seed per gram is generally in the seed catalogue, therefore, the germination rate should be examined in the field.

g / seed requirement per m^2= Desired plants per m^2/ number of seed per g x typical percentage of field establishment x 1/100.

There has been little information available describing seed mixtures for herbaceous perennials on green roofs. This research focused on the germination and chilling requirements of certain plants because the fundamental success of an extensive green roof depends on the establishment and development of the plant material (Emilsson and Rolf, 2005).

1.5 Research questions

The research questions included:

1) Which species (native and non-native) have potential for use in green roof seed mixes taking account the known germination requirements and cost of seeds?
2) Which of these selected species germinate readily from seed?
3) Which of these selected species require chilling before germination?
4) Is there any relationship between seed size and germination rate?

2. Materials and methods

The experiment was carried out on the fourth story of a commercial building in the city centre of Sheffield UK. The plants selected originate from dry habitats, such as the stony, sandy or calcareous soils of Europe's dry grasslands. Because of their drought tolerance, shallow roots and low growing forms, these species might adapt to the green roof environment and could be candidates for use on extensive green roofs. Some of the species are already commonly used on extensive green roofs (*Achillea, Centaurea, Dianthus, Hieracium*, *Festuca* and *Stipa).* The plants selected for this study are listed in Table 3.1.2 and their characteristic was summarized as below.

Table 3.1.2 Characteristics of used plant species in this experiment

Botanical Name	Family	Distribution	Typical Habitat	Height	Flower colour	Flower season
Forbs						
Achillea ageratifolia	Compositae	Balkans	Rocks and scrub	30 cm	White	July-Aug
Achillea erba-rotta ssp moschata	Compositae	Central Alps	Rocky slopes, alpine grassland and calcareous soils in the Alps	10 cm	White	June
Achillea millefolium	Compositae	Europe to W Asia, widely naturalized in Temperate regions	Meadows and pastures, grassy banks, hedgerows and waysides, the poorest soils	to 60 cm	White	June-Sep
Achillea nobilis	Compositae	South and Central Europe, S USSR	Dry steppe	To 50 cm	White	Summer
Achillea tomentosa 'Aurea'	Compositae	SW Europe to C Italy	Introduced, grown in gardens and established in a few location in Scotland and N.E. Island	15 cm	Yellow	May-June
Acinos alpinus	Lamiaceae	Mountains of C & S Europe	Poor, stony soils	to 45 cm	Violet	June-August
Aethionema grandiflorum	Cruciferae	Iran, Iraq, Caucasia	Dry, rocky slopes	to 45 cm	Rose pink	May

Ajuga genevensis	Lamiaceae	Europe except S.W., North and S. W. Asia (S. Europe)	Grassland, stony ground on calcareous soils	to 40 cm	Bright blue	May-July
Allium schoenoprasum	Liliaceae	Europe, Asia, N. America	Naturally found in damp meadows in the mountains	10-60 cm	Rose pink	Summer
Alyssum argenteum	Cruciferae	South Alps, SE Europe	Sandy soil	to 45 cm	Deep golden yellow	June-July
Anacyclus pyrethrum var. *depressus*	Compositae	Morocco	Rocky slopes	1 cm/5 cm	White	April-May
Anacyclus pyrethrum var. *depressus compactum* 'Silberkissen'	Compositae	Mediterranean - Spain, Morocco and Algeria	Rocky slopes	5-20 cm	White	April-August
***Anthemis carpatica* 'Karpatenschnee'**	Compositae	Eastern Europe	stony slopes of the Alps	15 cm	White	Early summer
Anthemis tinctoria	Compositae	Native of most Europe, Turkey, the Caucasus, W Syria and Iran and naturalized in UK and North America	Roadsides, steppes, waste places and scrub	to 45 cm	Yellow	May-July(June-July)
Armeria maritima 'Alba'	Plumbaginaceae	North Europe	Dry meadows, often in the mountains	10-20 cm	White	May-July
Calamintha grandiflora	Lamiaceae	W.,S. and S.C. Europe, S.W. Asia and Algeria	Scrub and on dry banks, usually on limestone	to 60 cm	Lilac	June-Sep
Calamintha nepeta	Lamiaceae	S., W. and S.C Europe from W. and C. France to S. Russia; N. Africa, N. Syria and N. Iran	Dry banks, usually calcareous	to 50 cm	Light blue	August-Oct
Campanula rotundifolia	Campanulaceae	Native of UK, France only in the mountain, NW Germany, Denmark	Dry grassy places and on fixed dunes often in poor shallow soils	3 cm/20 cm	Light purple	June-August
Centaurea alpestris	Compositae	Europe	Alps, Carpathians, Pyrenees grassland	30-50 cm	Purple	Late spring summer
Centaurea scabiosa	Compositae	Europe	Grassland, roadside, hedge banks, scrub on calcareous soils	30-80 cm	Purple red	June-August
Centaurea pulcherrima	Compositae	Caucasus	rocky slopes	40 cm	Pink	June-July
Chrysanthemum leucanthemum	Compositae	Throughout British Island, Throughout Europe to Lapland; Siberia.	A common plant of grassland on all the better types of soil	40 cm	White	June-Sep
Dianthus amurensis	Caryophyllaceae	E Asia	Dry grassland	40 cm	Deep purplish pink to mauve	Summer
Dianthus carthusianorum	Caryophyllaceae	E and S Europe	Dry grassland	20-60 cm	Pink	May-Aug
Dianthus cruentus	Caryophyllaceae	Balkans	Steppes	5 cm/50 cm	Blood-red	June-July
Dianthus deltoides 'Brilliancy'	Caryophyllaceae	Most of Europe from Scotland eastwards to Finland and N Russia, but absent from Mediterranean?	Dry, grassy places	to 45 cm	Rose red	Summer
Dianthus pontederae	Caryophyllaceae	Turkey	Dry stony grassland	60cm	Purple-red flowers	June-August
Gypsophila repens	Caryophyllaceae	C and S Europe	Grassland and rocks	5cm/10cm	White	May-June
Hieracium alpinum	Compositae	Europe, Temperate Asia	Grassland	10-15cm	Yellow	Late summer
Hieracium aurantiacum	Compositae	Europe, W Asia	Roadside and railway banks	40cm	Orange-yellow	June-August
Hieracium intybaceum	Compositae	Europe	Mountain, Alps, grassland	1-30cm	Pale yellow	Summer
Hieracium lanatum	Compositae	Native of France and N Italy, in the Alps and the Jura	Limestone rocks and cliffs at 300-2100m		Yellow	May-July
Hieracium maculatum 'Leopard'	Compositae	western and central Europe	Rocks and on the top of walls	7-12 inches tall	Yellow	June - August
Hieracium pilosella	Compositae	Europe, Asia, Siberia	Grassy pastures and heath, banks, rocks, walls	3cm-8cm	Yellow	May-July
Jasione montana	Campanulaceae	Europe, especially near coasts, from W France to Denmark	Cliffs, dry grassland, dunes, on acid sandy or stony soils	to 30cm	Pale sky blue	May-August

Leontodon autumnalis	Asteraceae	Europe	Meadows, grassland, roadside, not usually calcareous and on serpentine rock	15-30cm	Yellow	June-Oct
Limonium bellidifolium	Plumbaginaceae	England in Norfolk and Lincolnshire only, SW and Mediterranean France	Sandy upper parts of salt-marshes	1.5-4cm	Pale pink	July-Aug
Limonium latifolium	Plumbaginaceae	Native of SE Europe from Bulgaria and Romania to S Russia	Steppe and dry grassland	to 60cm	Purple	July-Sep
Linum perenne	Linaceae	Native of most of Europe from England and Spain eastwards to Russia and C Asia	Grassland and dry subalpine meadows	to 60cm	Purple	May-July
Nepeta x faassenii	Labiatae	A hybrid between N. racemosa and N. nepeta, species from Europe and North America		to 30cm	Purple	May-July
Oenothera caespitosa	Onagraceae	Native of N Mexico and from California northwards on the east of the Sierras to Utah and E Washington	Dry stony slopes, in open scrub and pine woods in very dry areas, at 1000-3000m	Stemless or to 20cm	White, Fading pink	Flowers opening at night
Oenothera speciosa	Onagraceae	Native of Missouri and Kansas, South to Texas and Mexico, and naturalized in the other parts of SE US	Growing in dry fields and prairies	to 30cm	White or pale pink	Flowers opening at night, May-July
Origanum vulgare	Labiatae	Native of most of Europe, Turkey and C Asia eastwards to Taiwan	Dry grassy places or in the south, in open woods	20cm	Purple, pink or white	Sep-Oct
Potentilla argentea	Rosaceae	Europe	Dry sandy grassland	to 10cm	Yellow	June-Sep
Petrorhagia saxifraga	Caryophyllaceae	S and C Europe, Caucasus, Iran	Grassland	5cm/15cm	Pink	June-Sep
Primula veris	Primulaceae	Native of S. Russia and the Crimea, eastwards to Chinese Turkestan and South to N Iran to Turkey	Scrub by stream, in mountain meadow and among rocks	20cm	Yellow	May-June
Salvia pratensis	Labiatae	Most Europe northwards to N. Germany and N.C. Russia; Morocco	Meadows	50cm	Blue-violet	June-July
Saponaria ocymoides	Caryophyllaceae	SW Europe S Alps, Italy	Mountain	20cm	Pink	July
Silene uniflora	Caryophyllaceae	Europe	Sands and rocks	15cm	White	Summer
Teucrium chamaedrys hort	Lamiaceae	UK, France, Belgium	Calcareous grassland and rocks	5-10cm	Pinkish purple	June-Sep
Grasses						
Achnatherum calamagrostis	Poaceae	C, E and SE Europe	Mountains	100cm		June-Sep
Andropogon scoparius	Poaceae	N. America	prairies and open woods, dry fields and hills	90-120cm		July to Sept
Anthoxanthum odoratum	Gramineae	Most of Europe; Caucasus; N. Africa	In pastures and meadows and on heaths and moors, equally commonly on acid or basic soils.	10cm-40cm		April to June
Bouteloua gracilis	Poaceae	S. and W. USA, Mexico	Dry, sandy plains	20cm		July to August
Briza media	Gramineae	Most of Europe, except the Arctic and parts of south; temperate Asia	In meadows and grassy places. Occurring in varied habitats, ranging from wet and acid to dry and calcareous	20cm-40cm		June-August
Festuca amethystina	Poaceae	Alps, SE Europe, Asia Minor	Dry grassland, roadsides and wasteland	30cm/40cm		June
Festuca glauca	Poaceae	S, C and E Europe	Widely grown in parks and gardens throughout the British Isles for ornament but not known to be naturalised.	20cm/40cm		May-June
Festuca valesiaca 'Glaucantha'	Poaceae	E. Europe	Dry grassland, roadsides and wasteland	10cm/25cm		June
Melica ciliata	Poaceae	Europe, SW Asia	Limestone rock grassland	70cm		June
Stipa barbata	Poaceae	South Europe	Steppe	80cm		June-July
Stipa pennata	Poaceae	C and SE Europe, W Asia	Dry sandy areas	80cm		May-June

Stipa tenuissima	Poaceae	C and S Europe, S Russia, Siberia, Turkey, Caucasus	Prairie	100cm		July-Aug

(Adapted from Brickell, 2003, Clapham et al., 1987, Hausen and Stahl, 1993, Kingsbury, 1996, Preston, et al., 2002)

All seeds were obtained from Jelitto Perennial Seeds (Schwarmstedt, Germany)10 seeds of 62 species were sown in 9 cm pots on 26th May, 2004 (spring sowing). Because the seed sizes of *Stipa barbata* and *S. pennata* were big and their numbers were limited, only 5 seeds were sown for those species. The propagation soil was John Innes No. 1. After sowing, the seeds were covered with gardening gravels to create the appropriate shade for germination. Each species was tested in three replications, for a total of 186 pots. The pots were placed on the big trays for subsurface irrigation. The germination rate for each pot was measured every two weeks from 10th June to 22nd July 2004 for a total of four observations.

In the autumn, the same experiment was repeated to study the chilling requirement for 18 species which had germination rates of less than 30% in spring sowing. On 12th December 2004, seeds which highlighted species in Table 3.1.2 were sown again. The seeds were kept in the refrigerator (4°C) from spring to 12th December. The plants were left on the roof over the winter without irrigation since they had enough rain. From March 2004, the plants were watered once a week so that the soil had always enough water. The germination rate of plants in each pot was measured every two weeks from 17th March to 21st April 2005 for a total of four observations. For germination rate, the statistical analysis was not performed. The relationship between weight of seeds (mg) and germination rates of forbs and grasses (%) was examined only for the spring sowing. The amount of seeds per gram was obtained from the Jelitto catalogue (2002). To detect the relationship between seed size and germination rate in spring, ANOVA was used to test the significance of the regression line. Statistical analysis was performed using Minitab 14.

Fig.3.1.1. Overview of germination trial

3. Results

3.1 Germination rate in spring and autumn sowing

The mean final germination rates of individual plants in spring and autumn sowing are shown in Table 3.1.3. The results show a wide range of germination rates ranging from 96.7% to 0%. Many species had high germination rates in spring sowing, and the majority of seeds germinated 14 days after seeding. *A. schoenoprasum, N. × faassenii, L. perenne, M. ciliata, S. ocymoides, A. pyrethrum* var. *depressus* and *D. carthusianorum* had germination rates of over 80%. Most of the 18 species which were sown again in autumn had equal or less germination rates compare to the spring sowing (i.e. less than 30%). Six of those species (*A. erba-rotta* ssp. *moschata, P. argentea, S. pennata, H. alpinum, P. veris, S. barbata*) had higher germination rates after chilling but, aside from *Stipa* spp., their germination rates were still low and the plants were small. These results suggest that many plants which have potential use for green roofs in the UK do not require chilling, and that spring sowing would yield the best establishment.

Table 3.1.3 Final germination rates of study plants from spring and autumn sowing.

Latin name	Family	Growth form	Germination rate in the spring (%)
A. schoenoprasum	Liliaceae	Forbs	96.7
N. × faassenii	Labiatae	Forbs	96.7
L. perenne	Plumbaginaceae	Forbs	90.0
M. ciliata	Poaceae	Grass	90.0
S. ocymoides	Caryophyllaceae	Forbs	86.7
A. pyrethrum var. depressus	Compositae	Forbs	80.0
D. carthusianorum	Caryophyllaceae	Forbs	80.0
C. pulcherrima	Compositae	Forbs	76.7
P. saxifraga	Caryophyllaceae	Forbs	76.7
A. argenteum	Cruciferae	Forbs	73.3
C. scabiosa	Compositae	Forbs	73.3
D. amurensis	Caryophyllaceae	Forbs	70.0
S. tenuissima	Poaceae	Grass	70.0
A. tinctoria	Compositae	Forbs	66.7
C. leucanthemum	Compositae	Forbs	66.7
G. repens	Caryophyllaceae	Forbs	66.7
A. pyrethrum var. depressus compactum 'Silberkissen'	Compositae	Forbs	63.3
C. alpestris	Compositae	Forbs	63.3
D. cruentus	Caryophyllaceae	Forbs	63.3
F. amethystina	Poaceae	Grass	63.3
F. glauca	Poaceae	Grass	63.3
F. valesiaca 'Glaucantha'	Poaceae	Grass	63.3
A. maritima 'Alba'	Plumbaginaceae	Forbs	60.0
L. bellidifolium	Plumbaginaceae	Forbs	56.7
L. latifolium	Plumbaginaceae	Forbs	56.7
T. chamaedrys hort	Lamiaceae	Forbs	56.7
A. grandiflorum	Cruciferae	Forbs	53.3

A. scoparius	Poaceae	Forbs	53.3	
A. odoratum	Gramineae	Grass	53.3	
D. deltoids 'Brilliancy'	Caryophyllaceae	Forbs	53.3	
D. pontederae	Caryophyllaceae	Forbs	50.0	
H. lanatum	Compositae	Forbs	46.7	
B. gracilis	Poaceae	Grass	43.3	
A. millefolium	Compositae	Forbs	40.0	
A. tomentosa 'Aurea'	Compositae	Forbs	36.7	
A. carpatica 'Karpatenschnee'	Compositae	Forbs	36.7	
H. maculatum 'Leopard'	Compositae	Forbs	36.7	
S. pratensis	Labiatae	Forbs	36.7	
B. media	Gramineae	Grass	33.3	
H. aurantiacum	Compositae	Forbs	33.3	
H. intybaceum	Compositae	Forbs	33.3	
H. pilosella	Compositae	Forbs	33.3	
O. speciosa	Onagraceae	Forbs	33.3	
S. uniflora	Caryophyllaceae	Forbs	33.3	**Germination rate in the autumn**
A. alpinus	Lamiaceae	Forbs	26.7	26.7
A. calamagrostis		Grass	23.3	0
C. rotundifolia	Campanulaceae	Forbs	23.3	0
A. nobilis	Compositae	Forbs	20.0	6.7
O. caespitosa	Onagraceae	Forbs	16.7	6.7
A. erba-rotta ssp *moschata*	Compositae	Forbs	13.3	16.7
C. nepeta	Lamiaceae	Forbs	13.3	0
L. autumnalis	Asteraceae	Forbs	10.0	0
A. ageratifolia	Compositae	Forbs	6.7	3.3
O. vulgare	Labiatae	Forbs	6.7	6.7
P. argentea	Rosaceae	Forbs	6.7	16.7
C. grandiflora	Lamiaceae	Forbs	3.3	3.3
S. pennata	Poaceae	Grass	6.6	46.7
J. montana	Campanulaceae	Forbs	3.3	0
A. genevensis	Lamiaceae	Forbs	0	0
H. alpinum	Compositae	Forbs	0	3.3
P. veris	Primulaceae	Forbs	0	3.3
S. barbata	Poaceae	Grass	0	73.3

3.2 The relationship between seed weight of forbs and germination rate in the spring sowing

The results indicate a significant positive relationship between seed weight of forbs and germination rate (y=34.28+3.207x, $p<0.05$, R^2=58.2 %) (Fig.3.1.2). Although germination rates varied widely for seeds of the same weights, there was a trend that smaller seeds had lower germination rates. Species with small seeds, such as *Hieracium* spp. and *Achillea* spp., had lower germination rates while species with larger seeds, like *Centaurea* spp., had higher germination rates. Interestingly, the seeds with the highest germination rates (*A. schoenoprasum* and *N. x faassenii*) were rather small, only 3mg in size. This trend was not observed between grass species, however, probably because two species *S. barbata* (100 mg) and *S. pennata* (75 mg) were significantly bigger than the other species and they had low germination rates.

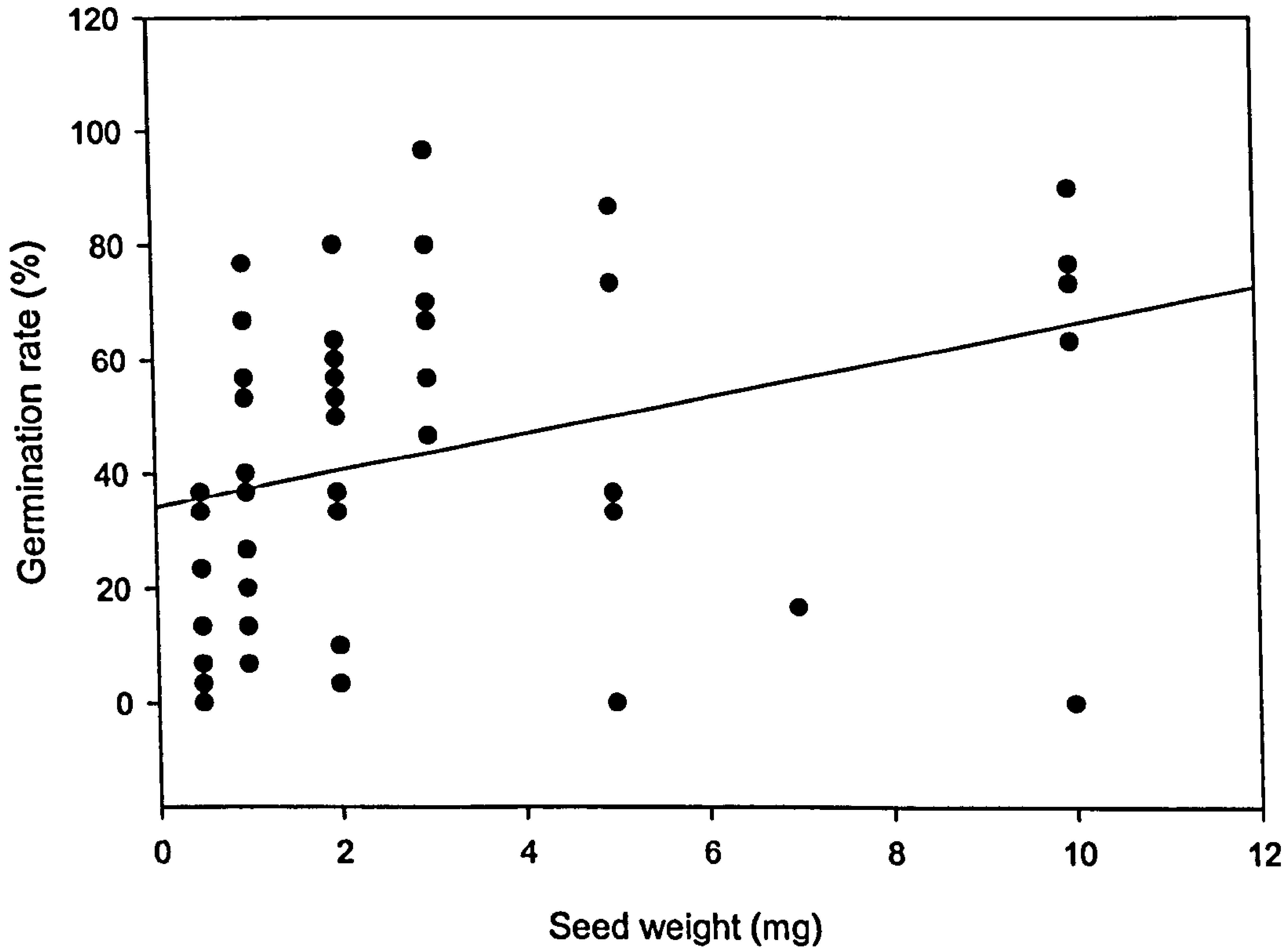


Fig.3.1. 2 The relationship between seed weight (mg) and germination rate (%) in the spring sowing (Forbs) (y=34.28+3.207x, $p<0.05$, R^2=58.2 %)

4. Discussion

4.1 Germination rate

Many of the plants studied here had high germination rates in the spring, and the majority of them germinated within two weeks of sowing. This suggests that they do not require chilling and they germinate in moist soil as soon as they experience high enough soil temperatures. They are generally straightforward to establish by field sowing (Hitchmough, 2004d). For these non-dormant seeds, maximum germination in the shortest time occurs when provided with optimum temperature and sufficient water (Probert, 2000). This strategy, in which the seed population begins and completes germination very uniformly, tends to be observed in fast-growing species that can rapidly exploit the conditions favourable for germination (Larcher, 2003). In Mediterranean and arid environments, an early growth advantage may be especially important for perennial species that must grow sufficiently large in the spring to endure 6-8 moths of summer drought (Dyer et al., 2000).

The results showed a wide range of germination rates between plant species. The key to the longevity of a green roof is rapid plant establishment (Snodgrass and Snodgrass, 2006), and well-established plants are more likely to survive winter and drought than plants that were poorly established (Thuring 2005). Seed specifications for green roofs should include rapidly germinating seed that do not require special treatments like scarification or cold or warm storage periods (Snodgrass and Snodgrass, 2006). The species which showed high germination rates in this study could be reliable in seed mixtures. Snodgrass and Snodgrass (2006) also observed that *Petrorhagia* and *Dianthus* species germinate rapidly and have potential for seed propagation for green roofs. In this study, these species demonstrated relatively high germination rates: *P. saxifraga* 76.7 %, *D. carthusianorum* 80.0 %, *D. amurensis* 70.0 %, *D. cruentus* 63.3 %, and *D. deltoides* 'Brilliancy' 53.3 %. These species are commonly used for extensive green roofs in Europe and eastern North America, and this study confirmed the possibility using these species from seed mixture in the UK.

Angevine and Chabot (1979) pointed out that germination characteristics cannot be classified according to habitat since there may be more than one germination pattern. However, the germination characteristics of the endemics are very similar to geographically widespread members of the same genus (Baskin and Baskin, 1988). Seeds may utilize certain types of environmental control of dormancy and/or germination to optimise the season of germination. Light, moisture and temperature are the important environmental factors controlling seed germination. Change in temperature would provide the most reliable seasonal signals (Washitani and Masuda, 1990). Grime et al. (1981) tested 403 species of germination characteristics in a local flora. Rapid germination and high initial germinability was characteristics of the species of greatest abundance in the Sheffield flora. In this experiment, their habitats were similar, however, tendency was observed that the species from calcareous soil showed a low percentage of germination (e.g. *A. erba-rotta* spp. *moschata* 13.3 %, *A. genevensis* 0 %, *C. grandiflora* 3.3 %, *C. nepeta* 13.3 %). On the contrary, some species from mountain areas showed high germination rate (e.g. *A. schoenoprasum* 96.7 %, *A. maritima* 'Alba' 60.0 %), although there were exceptions (e.g. *P. veris* 0 %). Various percentages were observed in grassland and meadow species.

Generally, Compositae which come from climates with a predictably warm springs and summers are fast-growing species which germinate readily (Grime et al, 1988, Kingsbury 1996). Of the several Compositae studied here, *A. tinctoria, C. leucanthemum, Anacyclus spp.* and *Centaurea spp.* showed relatively high germination rates although *Achillea* ssp. and *Hieracium* spp. had lower rates. These 2 species may still be considered for inclusion in seed mixtures, but it would be necessary to add higher percentages of seeds. According to some previous research, most *Campanula* spp, *C. scabiosa, O. vulgare* (Hitchmough, 2004d), *A. millefolium, B. media, C. leucanthemum* (Baskin and Baskin, 1988) do not fall into dormancy. Their germination rates here were 23.3 %, 73.3 %, 6.7 %, 40.0 %, 33.3 %, and 66.7 %, respectively. O.

vulgare had very low germination rates both after spring and autumn sowing. In the study of Grime, et al. (1981), *O. vulgare* showed high germination rate (89 %) in Petri dish. Probably the low germination would concur with a study that observed high mortality by this species in a study of germination and mortality in a chalk grassland in the Netherlands (Pons, 1991).

According to Grime et al. (1981), the species which response to chilling treatment can be divided into two categories, in the first of which the seeds are comparatively large and after chilling are capable of rapid germination at low temperature and in darkness. It seems likely that the large seeds and capacity for early germination allow seedling of these species to compete effectively with neighbouring established perennials. The other categories is that the requirement of chilling is allied to a need for subsequent exposure to light or higher temperature or both and it is involved in the mechanism of delayed germination and seed burial. *S. pennata and S. barbata*, which were relatively large seeds in this study, showed higher germination rates after being treated with their chilling requirements. It is considered that these species may belong to the former category. If these species are to be used in seed mixtures, they would be chilled in the fridge and can be sown with other no dormant species in the spring.

As shown in Table 3.1.3, most of the species which had less than 30 % germination rates after spring sowing had low germination rates in the autumn as well. According to Bewley and Black (1994), a high proportion of species can be released from dormancy when they experience relatively low temperatures, generally in the range 1-10 °C but in some cases as high as 15 °C . In addition, the requirement of duration of chilling is different from species. Some of species might not have long enough chilling or water for germination because of mild climate of UK. Moreover, the water availability in the soil may be not appropriate for some species. The species such as *J. montana, A. genevensis, H. alpinum, P. veris* were probably lacking some requirements for germination in this experiment. They should not be used for seed mixtures because the percentage of seedling emergence tends to be low and extended over a period of time (Hitchmough, 2004d). In this study, *P. veris* showed low germination rates of 0 % and 3.3 % in spring and autumn sowings, respectively. Grime et al. (1981) also showed that 0 % of germination freshly collected seeds. Generally, *P. veris* adapts well to the green roof environment, however, using plug plants rather than seed sowing is recommended. *H. aurantiacum* is known to require cold stratification (Baskin and Baskin, 1998). *H. aurantiacum* showed more than 30% in spring sowing in this study, therefore, it was not repeated in autumn sowing. However, this species might have shown higher germination rates in autumn sowing if it had been repeated because it would fulfil the cold stratification.

4.2 Seed size

Forbs which were used in this experiment have small seed sizes (0.5 mg-10 mg). Although the range of weights for the seeds was small, the bigger sizes had higher germination rates than smaller sizes. It is generally assumed that the probability of seedling establishment depends greatly on seed size, e.g. amount of reserves accumulated for early seedling development (Haig and Westoby, 1988). Improved nitrogen and mineral nutrition is additional advantage in larger seeds in low-fertility soils (Lee and Fenner, 1989), and may be importance in xeric habitats with poor soils (Kigel, 1995). Michelle and Westoby (1994) studied 18 species of tree, shrub, forb, grass and climber from semi-arid Australia with seed weights ranging from 0.06 mg- 22.2 mg). They found that seedlings from large seed sizes had higher percentage of emergence than small seeded seedlings in the field. Hitchmough et al. (2003) suggested that small seeded species exhibit lower establishment than large seeded species. Generally, seed mixture is determined by seed weight, which seems to compensate for establishment success. However, there is the case that smaller seeds demonstrate high emergence, for example, *P. saxifrage* (1 mg) showed 76.7 % germination rate. Not only seed size but also the amount control of individual species by germination rate is essential.

4.3 Recommended seed mixture

The recommended seed mixture was formulated through the process by Hitchmough (2004d). Generally, a total plant target would be between 100 and 200 plants/m^2. Sometimes, it may be required to have more or less even numbers of plants of each species in vegetation, however this would be unsatisfactory since they will lose the rhythmic emergent qualities and will end up with a dense stand. It is better to decrease the tall emergent plants and increase the numbers of key species, such as long flowering season. From the result of this experiment, the recommended seed mixture for extensive green roofs is formulated as Table 3.1.4. Basically, the species which showed higher germination rate in the spring sowing were chosen. However, if the price was high or same species with similar foliage and flowers was replicated, these plants were removed from the list. In addition, the following criteria were considered: 1) Key species (long flowering season), 2) Reproduction (invasiveness), 3) Plant height and final size. Firstly, the number of key plant species for green roofs such as *A. schoenoprasum A. maritima* 'Alba' *C. leucanthemum D. carthusianorum G. repens* and

N. x faassenii was increased. Moreover, the number of slow growing species such as *A. maritima* 'Alba' *and G. repens* was increased. On the contrary, the number of self-seeding plants such as *P. saxifraga* and *A. tinctoria* (McIntire, 2005) and the number of big size plants such as *A. argenteum and C. scabiosa* was reduced. Generally, the number of grasses was limited to be smaller number than forbs because they tend to spread quickly and they can be invasive. No grass species are contained in here because they tend to spontaneously be colonized. According to the result of the germination rate, 0.57 g of seeds in total was required. However, this is the condition under the enough irrigation and more seeds may be required for the dry environment.

Table 3.1.4 The recommended seed mixture

Plant name	Desired plants/m^2	Number of seed per g	Germination (%)	g seeds/m^2	Percentage per weight
A. millefolium	10	1000	40.0	0.004	0.7
A. grandiflorum	10	500	53.3	0.01	1.9
A. schoenoprasum	12	333	96.7	0.03	6.1
A. argenteum	9	200	73.3	0.03	5.8
A. depressus	9	500	80.0	0.01	2.5
A. tinctoria	9	1000	66.7	0.01	1.1
A. maritima 'Alba'	13	500	60.0	0.02	2.7
C. alpestris	9	100	63.3	0.06	10.0
C. leucanthemum	10	333	66.7	0.02	3.5
D. amurensis	9	333	70.0	0.02	3.3
D. carthusianorum	9	333	80.0	0.02	3.8
G. repens	13	100	90	0.12	20.5
H. lanatum	10	333.3	46.7	0.01	2.5
L. latifolium	10	500	56.7	0.01	2.0
L. perenne	9	100	90.0	0.08	14.2
N. x faassenii	12	333	96.7	0.03	6.1
P. saxifraga	9	1000	76.7	0.01	1.2
S. pratensis	10	200	36.7	0.02	3.2
S. ocymoides	9	200	86.7	0.04	6.8
T. chamaedrys hort	9	333	56.7	0.02	2.7
Total	200			0.57	100

5. Conclusion

Many of the plants studied here, which have potential for use in extensive green roofs, do not require chilling for germination and had high germination rates in spring. The results suggest that spring might be the best season for direct sowing on the roofs for quick establishment. Out of 18 species which had germination rates of less than 30% in spring sowing, only six species (*A. erba-rotta* ssp. *moschata, P. argentea, H. alpinum, P. veris, S. barbata, S. pennata*) had higher germination rates after chilling but, aside from the two Stipa spp., the plants produced small shoot biomass. The plants with high germination rates, such as *A. schoenoprasum, N. x faassenii, L. perenne, M. ciliate, S.*

ocymoides, A. depressus, and *D. carthusianorum,* could be recommended for seed mixture in central UK. On the other hand, plants with low germination rates like *J. montana, A. genevensis, H. alpinum, P. veris* would best be excluded from green roof seed mixes. Between the forbs, there was a positive relationship between germination rate and seed size. However, because some species did not follow this rule, they should be considered individually. Sufficient water was available for this experiment, and irrigation methods during the establishment for seed mixture might be a future consideration. For further research, the different seed mixtures under different watering regimes would be necessary since drought can be a key factor for establishment. Plant competition within seed mixtures, and combinations with annuals or geophytes will also be important considerations. Finally, the long-term changes in dormancy and survivability of seeds would serve important insight since this study only covered the establishment phase.

3-2 Extensive green roof using annual plant species in the UK: Effect of sowing rate and supplementary watering

Abstract

Annual plants (plants which complete their entire life history within a year to adapt to short favourable periods in disturbed environments) have much potential for use in such contexts in created landscapes. Direct-sowing of annuals mimics the way that annuals establish themselves in the wild. The advantage of direct-sown annual plants are quick establishment, long flowering, beautiful colour of flowers, cost effectiveness and providing food resources for biodiversity. However, there has been little study of annual plants on extensive green roofs. This study investigated the emergence, growth and flower performance of annual including native and non-native species on an extensive green roof in Sheffield UK. The purpose was to see whether it is possible to establish the annual plant species from seed mixture, and to evaluate successful species, determine appropriate sowing rate and watering in the first growing season. The emergence, growth and flowering performance of annual plants were investigated on an extensive green roof in Sheffield UK. The 22 species seed mixture was sown in an experimental green roof with substrate depth of 7 cm under two sowing rates (2 g/ m^2 and 4 g/ m^2) and watering regimes (with and without supplemental watering every week). The result confirmed that annual seed mixtures are suitable for extensive green roofs; they are easy to install, have cheap and quick establishment (they started flower after one month of sowing), and the plant species were drought tolerant and had a long flowering period (more than 4 months). A low sowing rate could be better than a high sowing rate to reduce competition among sown species and result in good individual plant growth when they have enough watering. On the contrary, a high sowing rate is recommended for dry environment to have sufficient plant number. Watering was important for emergence and early growth and supplemental watering improved the growth of most of the species as well as their flowering performance. Successful species, which showed high germination rate, good growth and long flowering performance in this first growing season include *Alyssum maritimum, Coreopsis tinctoria, Echium plantagineum* 'Blue Bedder', *Gypsophila muralis, Iberis amara, Iberis umbellata* 'Fairy', *Linaria elegans* and *Linaria maroccana*. Least successful species were *Adonis aestivalis, Anagallis arvensis, Consolida regalis, Eschscholzia californica, Geranium molle* and *Viola tricolor.*

1. Introduction

1.1 Definition of annual plants

An annual is usually defined as a plant which completes its entire life history within a year. They germinate, grow and flower in the favourable season and they lie dormant as seeds in the harsh time of the year. This is an evolutional adaptation using phenology (Jones, 1983). They have adapted themselves to a brief growing season such as is found in the steppe and desert region of the world (Barber, 1954), and other habitats where a regular disturbance limits plant growth. In deserts and steppes severe seasonal drought restricts competition from perennial herbaceous plants other than bulbs, allowing the development of rich annual plant communities (Hitchmough, 2004d). A green roof environment has similar qualities to these mechanisms and the characteristics of annuals could be suitable for the harsh environment of extensive green roofs. However, there is little research about annuals for extensive green roofs although they have such potential. Kircher (2004) studied the effect of adding annual species as seeds to a sedum green roof over two years, as it was introduced in Chapter 2. Other authors have suggested that some annuals such as *Portulaca spp., Phacelia campanularia, Townsendia eximia, Eschscholzia californica, Tripleurospermum maritimum* could be potential for use in extensive green roofs (Dunnett and Kingsbury, 2004a and Snodgrass and Snodgrass, 2006)

1.2 Characteristics of annual plants

The annual plants have survival strategies of drought avoidance. There are two groups of annual plants that have been recognized: winter annuals and summer annuals. They germinate and complete their life cycles during the winter and spring months and during the summer and early fall months respectively (Mulroy and Rundel, 1977). The winter annuals as a group appear to be locally derived species and genera with their centres of distribution in the development of a Mediterranean climate in which the occurrence of precipitation coincides with the months of cool weather and summer drought (Johnson, 1968). Normally, winter annuals germinate between September and mid-December, but remain in a vegetative rosette or tuft until stem elongation takes place beginning in March or early April (Beatley, 1969). Summer annuals germinate typically after the first heavy rain in July or August and complete a full life cycle during the few summer weeks when soil moisture is available (Mulory and Rundel, 1977). The germination of many desert annual is controlled by internal mechanisms that response to temperature and moisture (Went 1948, Baskin et al. 1993). The main wild localities of winter annuals are California and Baja California, Chile and South America, Mediterranean basin, South Africa, Southern and Western Australia whereas summer annuals are rich in Texas and Gulf coast, Mexico and Central America and, China and Himalayan foothills (Phillips and Rix, 2002).

The advantages of using annuals as landscape plants can be listed as follows (Dunnett, 1999, Dunnett, 2004c, Ruggiero and Christopher, 2000), and these also apply to their use on green roofs.

- There is little delay between establishment and final growth form
- Flowering is rapid
- Typically flowers continue all summer long
- The intensity of colour is unrivalled
- Direct-sown annuals are very cheap, compared to other planting methods
- The diversity of flowers providing food resources for butterflies and other insects, and seedheads attracting winter birds

On the contrary, annual plants have a significant disadvantage that they are transient and, even with management to encourage regeneration from self-sowing seed, often require sowing again on a yearly basis (Hitchmough, 2004d). There is a careful balance to be achieved here between achieving a reasonable number of annuals from year to year and preventing the species from becoming weeds (Dunnett and Kingsbury, 2004a). In winter, although they have less visual interest, however, late flowers, seedheads and the dried skeletons of plants can have aesthetic value (Dunnett, 1999).

1.3 Usage of annual plants in landscape

Traditionally on the ground, annuals would be sown in interlocking single species drifts or blocks to produce an annual bed or border. However, this is time-consuming and it can result in a gappy or open structure to a planting if some species fail to establish. It also lucks a naturalistic, spontaneous effect (Dunnett, 2002). Because of these reasons, the vegetation created through direct sowing of mixtures of annuals would be a better option. In plant mixture, the increased productivity can be achieved by combining species of different height, growth form, phenology or rooting structure (Trenbath, 1974). Direct sowing is the simplest method and it is also the best method to fill large areas. To fill a square meter of garden with herbaceous perennial plants may cost around £20-25, although the cost of seed to cover the same area can be just 20-50p (Dunnett and Hitchmough, 2001). If the appropriate species were chosen, they may re-seed for year to year. Virtually, every kind of annual is suitable for direct sowing, as long as it can be sown at the proper time and it will germinate, and still have time to bloom before the weather gets too hot or too cold for it to survive. Some annuals such as *Alyssum* spp. bloom quickly and it takes about 8 weeks from germination to bloom (Freeman, 2000).

There are two ways to use annual plant mixtures on roofs: fillers, and natural planting using only annuals. Annual plants can be effective in filling gaps at one season or another. For example, early flower annual plants can accompany bulbs or fill empty areas between late flowering perennials. They are also useful to provide vitality and fill the ground in the first couple of years (Phillips and Rix, 2002). Snodgrass and Snodgrass (2006) recommended using a in the former way on green roofs because annual plants do not offer longevity. They also mentioned that annual plants can be incorporated into plant specifications as seasonal accents. Annual plant mixtures would be suitable when the natural display in quick establishment is necessary. Annual plants might be appropriate for use on temporary green roofs, such as those for festivals, because they provide rapid colourful flowering.

1.4 Annual plants for green roofs

Annual plants for green roofs should be drought tolerant and able to grow on shallow substrate depths. The most successful annuals for green roofs are those that will self seed from year to year once established. However, allowing plants to self-sow freely over a number of years can make each year's display unpredictable; this approach also demands a continual and sophisticated regime of dead-heading, thinning seedlings and the addition of new plants (Rice, 1999). Desirable traits also include a slender habit that does not crowd out or swamp other lower growing species and a compact habit that is not vulnerable to wind rock (Dunnett and Kingsbury, 2004a).

Although there are ready-made mixtures of native cornfield annuals, which include *Papaver rhoeas*, *Centaurea cyanus*, *Chrysanthemum segetum*, and *Agrostemma githago*, they are not always ideal as they tend to finish flowering before the end of summer (Dunnett, 2002), and they may be too big for green roof situations. Grass species may be kept to a minimum and used as flowering accents rather than as a ground covering matrix to avoid too much competition with the flowering annuals (Dunnett, 1999). A satisfactory annual plant mixture of both native and exotic species will begin flowering within 6-8 weeks of a spring sowing, and should continue in flower into the autumn. It should also remain in an attractive condition throughout time. To satisfy these requirements, the following categories of plants might be included (Dunnett, 2004c).

- Long-season species (providing a display over several months) e.g. *Centaurea cyanus*, *Chrysanthemum segetum*, *Linum grandiflorum* var. *rubrum*
- Rapid-flowering species (shorten the period between sowing and the beginning of an effective display) e.g. *Gypsophila muralis*, *Linaria maroccana*
- Late-flowering species (extend the life of a sown plant mixture into the autumn) e.g. *Centaurea cyanus*
- Emergent (provide visual and structural diversity). e.g. *Coreopsis tinctoria*
- Species with attractive seed heads (extend the season of display and provide structural interest). e.g. *Papaver somniferum*
- Star performers (Outstanding flowering or foliage attributes but may not have long display). e.g. *Iberis umbellata*

1.5 Establishment of annual plant seed mixture

Spring sowing will produce the most satisfactory results. Generally, a sowing rate of 3-5 g/m^2 will result in an effective density of plants (Dunnett, 1999). The germination performance of seed plays a major role in persistence and dynamics of annual plants in the field. In particular dormancy, which is controlled mainly by temperature and water availability, plays an important role in the fine-tuning of the temporal development of annual plant populations (Rivas-Arancibia et al., 2006), and improved flower colour displays (Rutledge and Holloway, 1994). Their research showed drought tolerance was different between species, and some species can establish, grow and flower under non-irrigated condition (Rivas-Arancibia et al., 2006). These species would be useful for use in landscape including green roofs.

1.6 Research question

Although they have such potential, there is little research about annuals for extensive green roofs. The aim of this study is to see whether it is possible to establish annual plant species from seed, and to identify successful species, appropriate sowing rates and watering regimes in the first growing season. The research questions in this study are:

1) Is it possible to have successful establishment, plant growth and flower performance using annual plant seed mixture on an extensive green roof ?
2) How do supplemental irrigation, sowing rate, and their interaction affect the emergence, growth and flowering of plant community and each species?
3) Which plants can survive during stressful periods without regular irrigation?
4) How competitive are the selected plants under different irrigation and sowing rate?

2. Materials and Methods

The experiment was carried out on the fourth story of a commercial building in the city centre of Sheffield UK. On the top floor of the building, which was surrounded by 0.345 m height of parapet, the extensive green roof was installed (Fig.3.2.1). Plots were framed by timbers and the build-up consisted of protective felt over the waterproofing, a root protection layer, a drainage layer and 7 cm of commercial green roof substrate (Zinco semi-intensive – based on crushed brick and 20 % organic content). The felt was used to protect the roof surface from the weight of timber and it also played a part in retaining moisture. Each plot was physically separate from the others (each plot size: 1 m x 2.2 m) to avoid the water travelling from one plot to another (Fig.3.2.2). Sowing rates of 2 g/ m^2 and 4 g/ m^2 were used, and plots were given supplemental irrigation or no supplemental irrigation. Three plots each were used for the watering regime and non-watering regime respectively, giving six plots in total. Each plot was divided into two subplots (each subplot size: 1 m x 1.1 m) by sowing rate, therefore, there were twelve subplots in total.

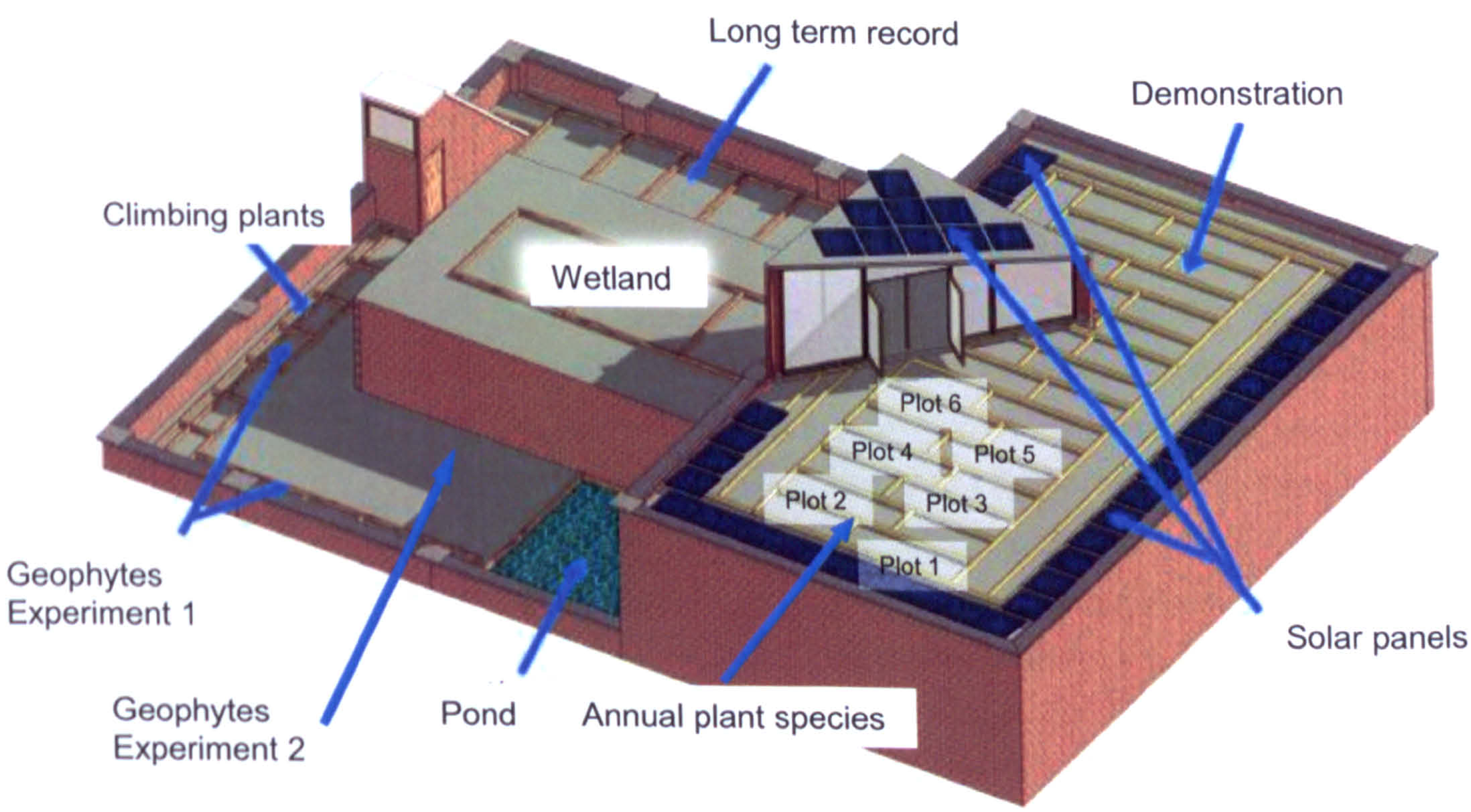


Fig.3.2.1 Overview of experimental site of the building (Source: Ark DM)

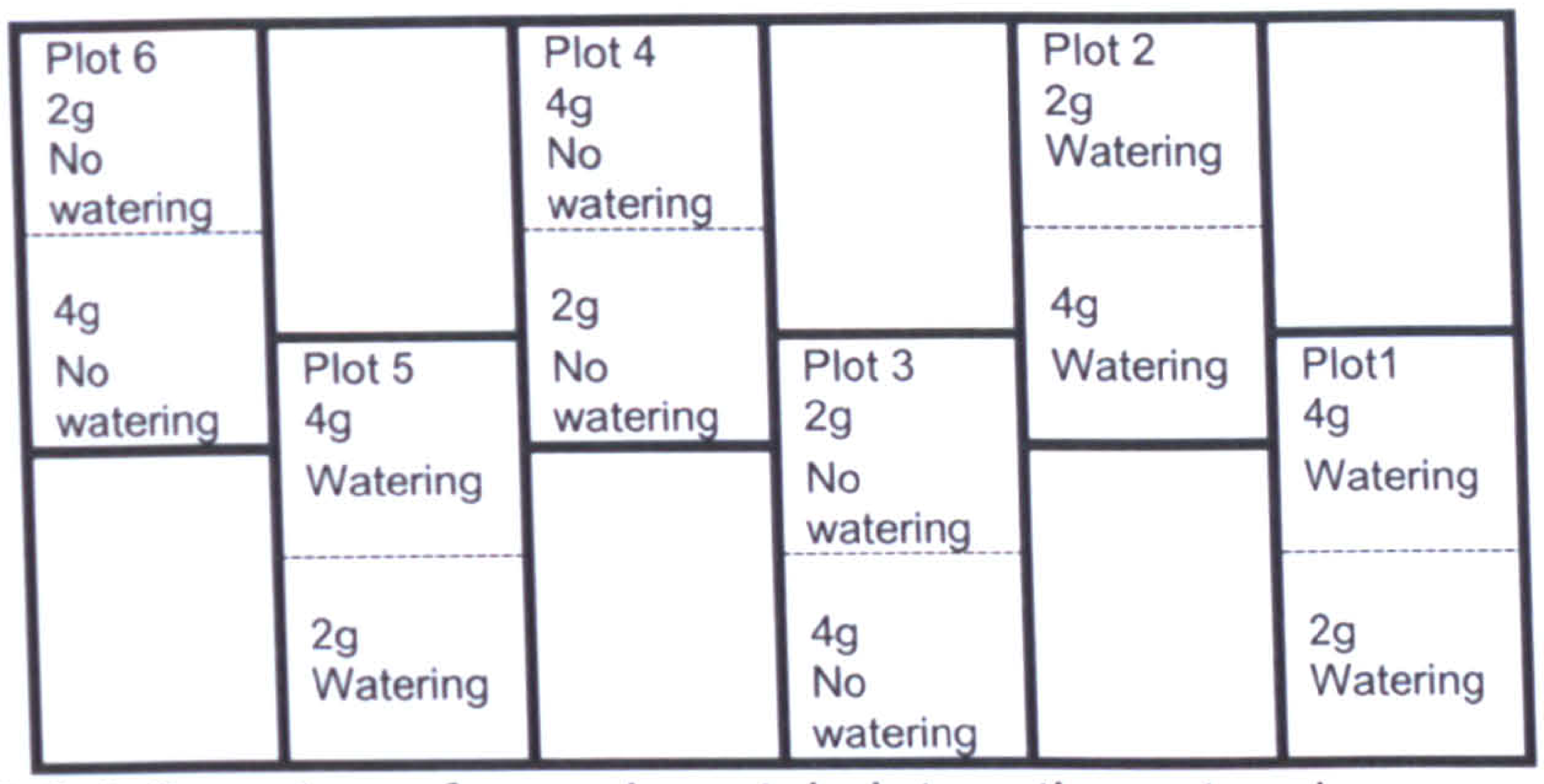


Fig.3.2.2 Overview of experimental plot on the extensive green roof

Fig.3.2.3 Overview of experimental plot on the extensive green roof

The annual mixture comprised of 22 species in equal proportion by weight in the mix, *Adonis aestivalis, Anagallis arvensis, Alyssum maritimum, Centaurea cyanus* (native form), *Chrysanthemum segetum, Convolvulus tricolor, Consolida regalis, Coreopsis tinctoria* (dwarf), *Echium plantagineum* 'Blue Bedder', *Eschscholzia californica, Geranium molle, Gypsophila muralis, Iberis amara, Iberis umbellata* 'Fairy', *Linaria elegans, Linaria maroccana, Linum grandiflorum* var *rubrum, L. usitatissimum, Papaver rhoeas, Reseda odorata, Tripleurospermum maritimum,* and *Viola tricolor*. These plants were predicted to adapt to the extensive green roofs because their habitats are seasonally arid, such as open ground, cornfield, grassland and sandy field. Species generally had a short height so that they can adapt the strong wind of rooftop condition. The plant characteristics are summarized in Table 3.2.1. and their pictures are shown in Table 3.2.2. The seed mixture was obtained from John Chambers wildflower seeds (Northamptonshire, UK). They were sown on 16^{th} June 2006. Some seeds are too small to be distributed over the substrate surface, therefore, it was mixed with building sand. 5000 mL of sand and seed mixture (20g and 40g of seeds respectively for the different sowing rates) were mixed well in the bucket. The area of each subplot was 1.1

m^2. The 500mL of sand with each density of seeds was distributed by hand. After sowing, the substrate was raked gently to incorporate the seeds into the substrate. The surface was levelled using the edge of rake. All plots were watered every other day until 13th July 2006 to make sure that germination occurred, and after this, the irrigation treatments were started.

Before watering, the moisture in the substrate was measured using moisture sensor (SM200 moisture sensor, Delta-T Devices Cambridge-England) every week. Three measurement points were randomly chosen from each subplot and there were six points in each plot, in total, eighteen points were measured for each watering treatment. The result of the moisture content was averaged and only when this showed less than 15%, water was applied as a fine spray from a handheld hose. The water was applied until the plot started to drain off the water. The mean of water content of substrate in both the watered plot and the non-watered plot was shown in Fig.3.2.4. From 13th July 2006 to 11th August 2006 a total of four watering were made. To test for significant differences in the moisture content between watering regime and no-watering regime, a T-test (Minitab Release 14) was used. Different capital letters indicate significant difference between the percentages of the moisture content. As shown in Fig.3.2.5 and Fig.3.2.6, June and July 2006 were very dry and warm months. The result showed the supplemental watering had significant effect even after one week later (Fig.3.2.4). In August there was more rain, however a low percentage moisture content was recorded until the middle of the month.

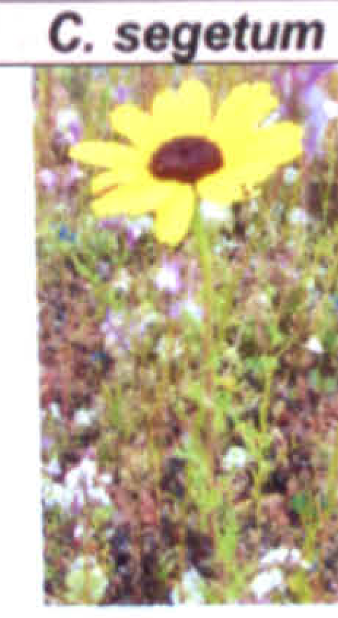
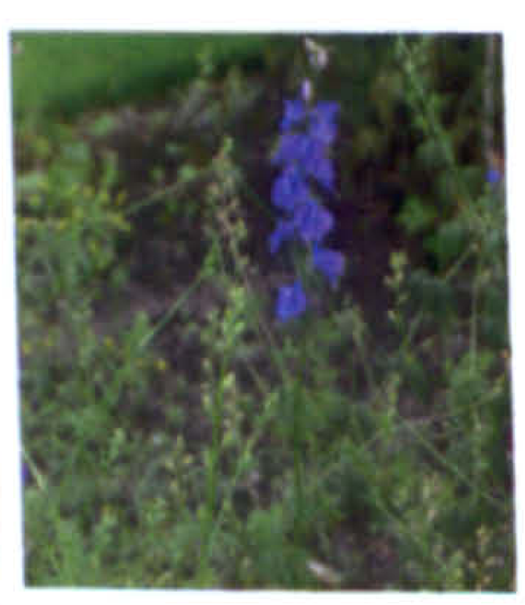
Table 3.2.1 Characteristics of the annual plant species used in this study

Species	Family	Native	Habitat	Height	Flowering	Seed size Seeds/g
A. aestivalis	Ranunculaceae	Europe from France and Spain eastwards to the Caucasus, Syria and Iran	Cornfields and waste grounds	≤50cm	May-July	85
A. arvensis	Primulaceae	Europe and Asia eastwards to Iraq and Afghanistan	Waste places, cornfields, sand dunes, rive banks	≤70cm	March-Sep	2500
A. maritimum	Cruciferae	Europe - Mediterranean. Naturalized in Britain	Dry sunny places in the Mediterranean	15-25cm	June - October	2500
C. cyanus	Compositae-Cardueae	Turkey	Pine forest, rocky slopes, cornfield	≤80cm	April-August	220
C. segetum	Compositae-Anthemideae	E Mediterranean, North Africa, Europe as far north and west as Scotland and Ireland	Acidic, sandy soil	20-60cm	June-August	600
C. tricolor	Convolvulaceae	Portugal and Meditteranean	Dry, open, grassy places	≤60cm	April- June	100
C. regalis	Ranunculaceae	SE Europe, eastwards to Iran and Turkmenia	Cornfields, steppe and west ground, at up to 1000m	≤40cm	June-Sep	750
C. tinctoria	Compositae-Heliantheae	North America, from Saskatchewan and Minnesota to Louisiana, Texas and Arizona	Moist low ground Roadsides and waste places	≤100cm	Midsummer	3000

E. plantagineum 'Blue Bedder'	Boraginaceae			≤40cm	June-Sep	250
E. californica	Papaveraceae	NW America from Washington to S Calfornia	Grassland, chaparral and desert up to 2000m		Feb-Sep	200
G. molle	Geraniaceae	Britain, Europe to the Himalayas	Dry grassland, dunes, waste places and cultivated ground	≤40cm	April - Sep	860
G. muralis	Caryophyllaceae	Much of C Europe (not the Mediterranean), the Caucasus and Siberia, and naturalized in eastern North America	Dry, sandy places	5-25 cm	July-Sep	380
I. amara	Cruciferae	W Europe from SE England and Germany and Italy	Chalky hills and cornfields	10-40 cm	May-Oct	400
I. umbellata 'Fairy'	Cruciferae	Native of the Meditteranean region from S France to Italy and Greece (I.umbellata)	Rocky places on limestone and serpemtine (I.umbellata)	15-25cm	May-Aug	430
L. elegans	Scrophulariaceae	N and C Spain and N Portugal	Grassy roadsides and among bracken in open pine forest	≤70cm	May-July	
L. maroccana	Scrophulariaceae	Morocco and North America	Open ground and sandy fileds	≤45cm	April-June	15000
L. grandiflorum var. *rubrum*	Linaceae	North Africa, California	Fields and wast places	≤60cm	March-May	350
L. usitatissimum	Linaceae	Not known as wild plant		40-90cm	June - July	300
P. rhoeas	Papaveraceae	Europe and North Africa, east across Asia to NW China, throughout temperate world	Cornfields, disturbed ground	≤100cm	Spring and summer	9000
R. odorata	Resedaceae	Eygipt, naturalized in the Mediteranean and California	Open ground	≤50cm	May-Sep	750
T. maritimum	Asteraceae	Eurasia, North Africa, North America	Common on stony ground by the sea	15-80cm	Jun–Sep	2000
V. tricolor	Violaseae	Most of Europe and Asia, southwards to C Turkey and eastwards to Siberia and Himarayas	Grassy places and arable fields	15cm	April-Sep	1000

(Adapted from Rees, 1995, Phillips and Rix, 2002, B&T world seeds 2007,)

Table 3.2.2 Pictures of the annual plant species used in this study

A.aestivalis	***A. arvensis***	***A. maritimum***	***C. cyanus***	***C. segetum***
				
C. tricolor	***C. regalis***	***C. tinctoria***	***E. plantagineum* 'Blue Bedder'**	***E.californica***
				
G. molle	***G.muralis***	***I.amara***	***I. umbellata* 'Fairy'**	***L. elegans***

(The pictures of *A.aestivalis, V.tricolor* from Phillips, R. and Rix, M.,2002, C.regalis from Van den Bos, 2008)

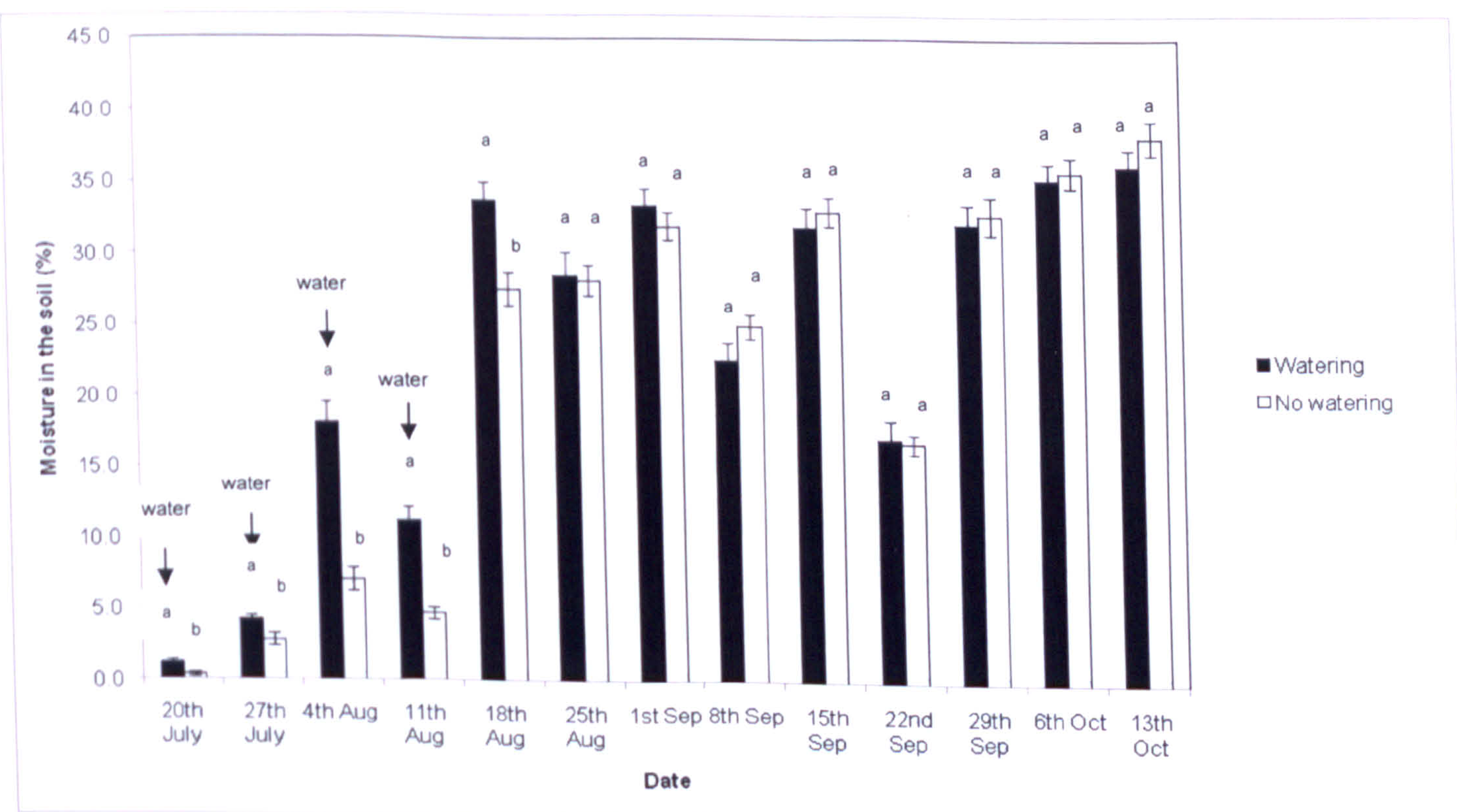


Fig.3.2.4 Mean water content of substrate (%) of the plots before watering in the watering and no watering regimes (n=18) Error bars represent standard error of the mean value. Means with the same letter do not differ significantly from each other.

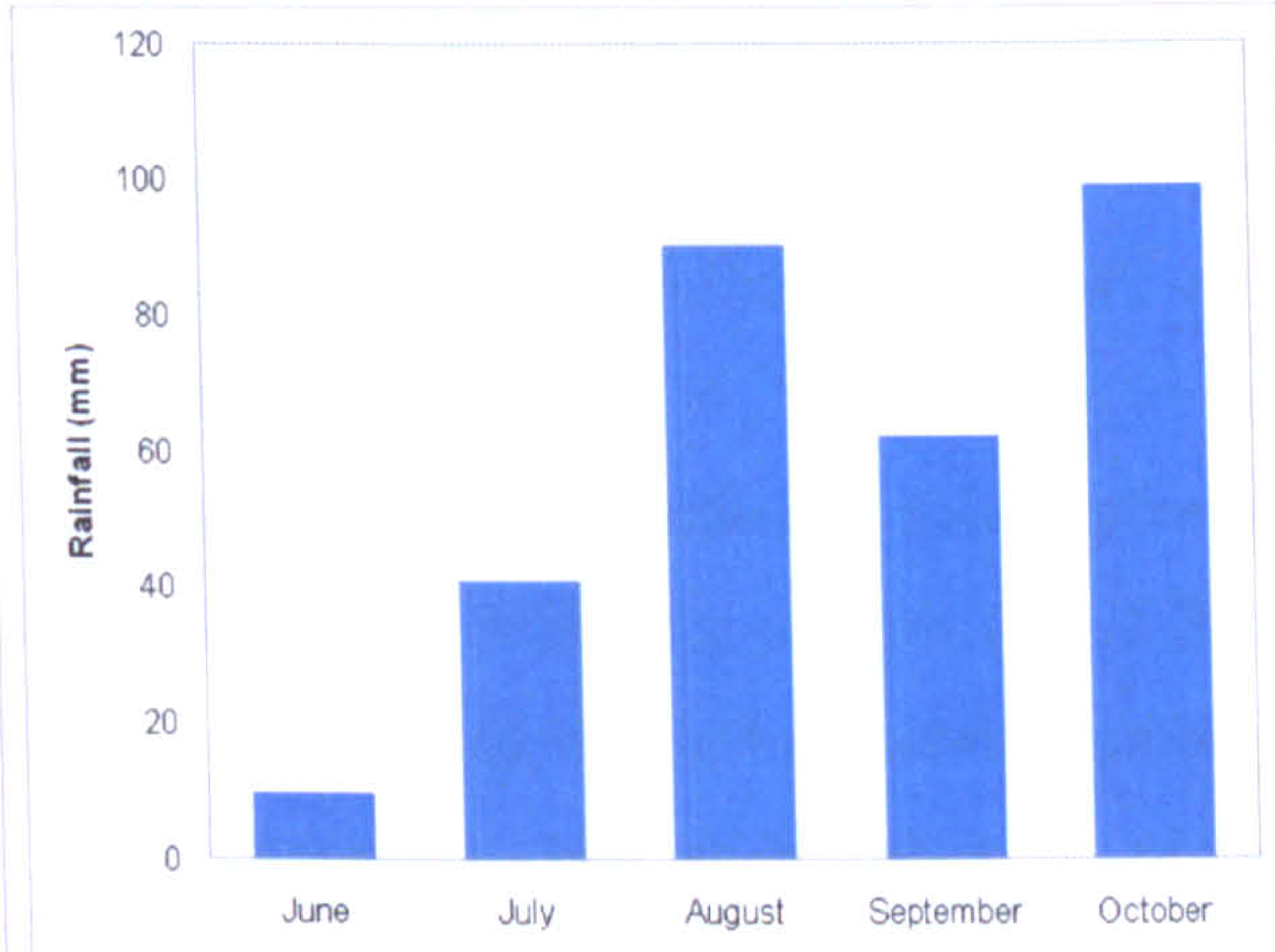


Fig.3.2.5 Mean monthly temperature change in 2006 in Sheffield (Source: Meto office)
Fig.3.2.6 Mean monthly rainfall change in 2006 in Sheffield (Source: Meto office)

Three quadrats (size: 30 cm x 30 cm) were set up randomly using sticks and strings for each subplot, there were nine quadrates for each treatment in total. The number of germinated seedlings of each species in the quadrat was counted every three weeks on 28th July, 18th August and 11th September 2006. The growth of 15 randomly selected plants of each of the 22 species (5 plants from each subplot) in each treatment was measured at the beginning and the end of August and at the end of September. The selected plants were marked and the same plants were measured. The measured parameters were height, shoot number and the diameter (average of the width and length) of the plants. The number of flowering plants of each species per subplot was counted every week. Also, to investigate the overview of annual plant growth over time, the photographs of each subplot were taken from the same positions. Harvesting took place at the beginning of October. The total emergence of each species per subplot was counted when they were harvested. The harvested plants were dried out in the green house until January 2007. Because of humidity in the green house, the shoots were additionally dried in a desiccator for one week before weighing. There was no temperature control for desiccator. The total dry shoot weight of all the plants from each subplot was measured and averaged. To test for significant differences between the treatments and the interaction, two-way ANOVA (Minitab Release 14) was used. When there were significant differences, means were separated by a Tukey test. Throughout the analysis, threshold for significance was set at $P<0.05$.

3. Results

3.1 Final shoot biomass and plant number

3.1.1 Final shoot biomass and plant number in total

Mean total dry weight of all species per subplot in relation to sowing rate and watering regime is shown in Fig.3.2.7. Although the mean total weight was higher in the watering than no watering regime, there were no significant effects of watering, sowing rate and interaction between these treatments. In the watering regime, the total dry weight was higher at low sowing rate (2 g/ m^2) than the high sowing rate (4 g/ m^2). However, in the no watering regime, the result did not show much difference between these sowing rates. Mean total plant number showed different pattern from dry weight (Fig.3.2.8). There was a significant effect of sowing rate, however, no significant effect of watering, or interaction between these treatments was observed. Larger number of plants emerged at the higher sowing rate. Interestingly, for the high sowing rate (4 g/ m^2), the total plant number was larger in the no watering regime than the watering regime although this difference was not significant. The larger number of plants with no watering was probably because there was less competition due to smaller individual plant size. From these two results, it is suggested that supplemental watering did not show significant improvement for the summary of final plant emergence and shoot biomass. In addition, each plant growth tended to be better in the low sowing rate since they showed higher dry weight although the total number of plants was smaller.

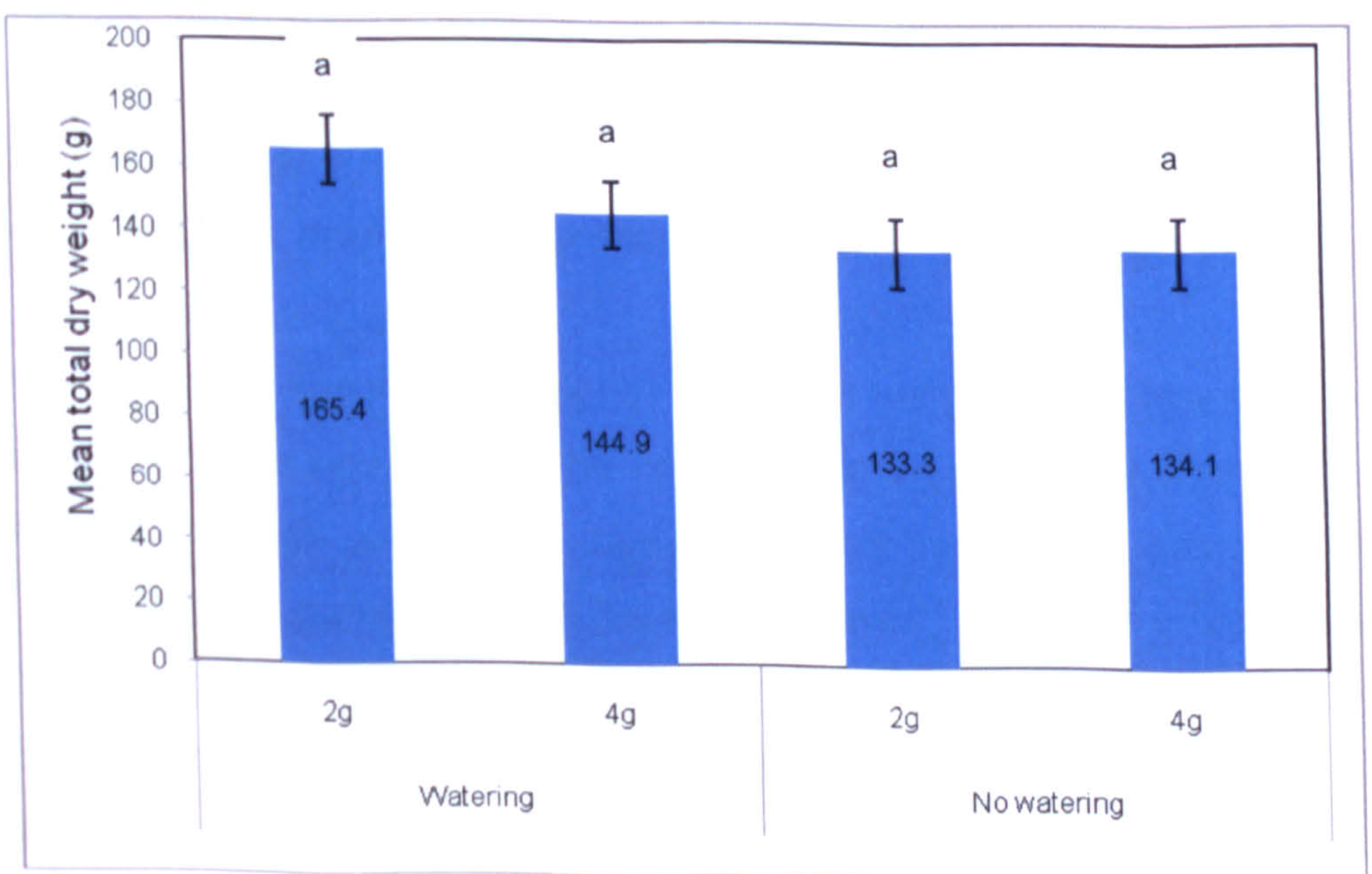


Fig.3.2.7 Mean total dry shoot weigth of all species per subplot(n=3)
Error bars represent standard error of the mean value. Means with the same letter do not differ significantly from each other.

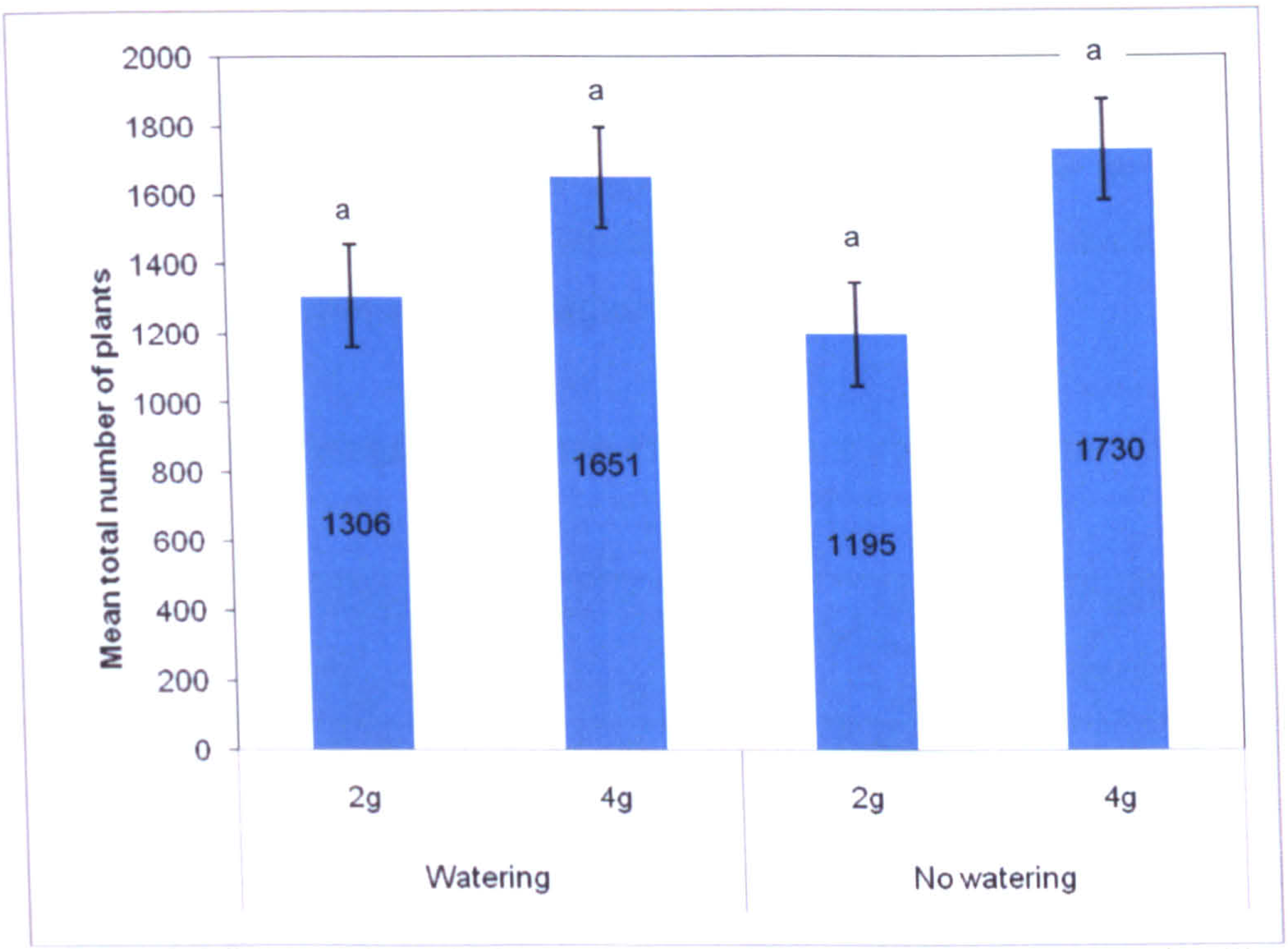


Fig.3.2.8 Mean of total plant number of all species per subplot(n=3)
Error bars represent standard error of the mean value. Means with the same letter do not differ significantly from each other.

3.1.2 Final plant number and shoot biomass in individual species

For the majority of species, watering, sowing rate and interaction between these treatments did not affect significantly the mean total dry shoot weight and the mean total number of plants per subplot (Table 3.2.3). In *C. cyanus, C. tinctoria, L. grandiflorum var rubrum* and *T. maritimum,* there was significant difference between watering on dry shoot weight. Sowing rate did not affect significantly dry shoot weight for any plants. In *A. maritimum*, *E. plantagineum* 'Blue Bedder', *G. muralis, I. amara* and *L. grandiflorum var rubrum,* the sowing rate had significant effect for mean total number of plants. In *E. californica,* there was significant effect of watering.

When watered, many species had higher dry shoot weight in the low sowing density. However, the opposite was true for the no watering regime; many species had higher shoot weight at the high sowing rate, again, probably because of less competition. In addition, a higher total number of species was observed in the high sowing rate in most species. These results might suggest that that individuals of many species could grow better at sowing densities of 2 g/ m^2 rather than 4 g/ m^2 in watering regime, whereas the growth was restricted at both densities in no watering. Greater shoot biomass was observed in higher density in no watering because the plant number is larger, rather than the result of individual plant growth.

There was considerable variation in dry shoot weight and number of plants between species. Only *A. aestivalis* did not germinate at all. *A. maritimum, G. muralis, L. elegans* and *L. maroccana* showed high dry shoot weight and large number of plants. Some species, such as *A. arvensis, G. molle, T. maritimum* and *V. tricolor* produced a large number of plants, however, their shoot biomass was small.

Table 3.2.3 Mean total biomass and mean total platns number of individual species per sub plot (n=3)

	Mean dry shoot weight per subplot (g)						Mean number of plants per subplot					
	Watering		No Watering				Watering		No Watering			
	2g	4g	2g	4g	SE	P	2g	4g	2g	4g	SE	P
A. arvensis	0.36 a	0.33 a	0.13 a	0.18 a	0.13	ns	31.33 a	46.00 a	20.00 a	35.00 a	10.48	ns
A. maritimum	22.66 a	23.36 a	22.35 a	21.13 a	3.61	ns	216.3 b	322.7 ab	192.7 ab	336.7 a	29.48	S<0.01
C. cyanus	1.28 a	2.39 a	0.51 a	0.98 a	0.42	W<0.05	8.67 a	16.00 a	6.67 a	12.67 a	3.87	ns
C. segetum	4.10 a	1.83 a	1.80 a	2.29 a	0.88	ns	12.00 a	15.00 a	6.67 a	12.67 a	3.00	ns
C.tricolor	0.39 a	0.65 a	0.31 a	0.37 a	0.18	ns	6.33 a	8.00 a	4.33 a	7.67 a	2.38	ns
C.regalis	0.07 a	0.04 a	0.03 a	0.05 a	0.02	ns	9.00 a	7.67 a	6.00 a	5.67 a	2.19	ns
C.tinctoria	8.11 a	6.45 a	3.10 a	3.70 a	1.14	W<0.01	65.33 a	81.00 a	41.00 a	68.00 a	9.40	ns
E. plantagineum 'Blue Bedder'	3.22 a	2.38 a	1.40 a	2.00 a	0.57	ns	10.00 b	18.33 a	8.67 b	15.67 ab	1.58	S<0.01
E. californica	0.29 a	0.18 a	0.07 a	0.12 a	0.08	ns	9.33 a	5.67 a	4.00 a	4.00 a	1.40	W<0.05
G. molle	1.69 a	1.32 a	0.76 a	1.25 a	0.54	ns	44.67 a	59.00 a	26.33 a	52.33 a	11.39	ns
G.muralis	16.64 a	11.87 a	11.57 a	11.87 a	2.87	ns	44.33 b	72.33 ab	47.67 ab	76.33 a	6.81	S<0.01
I. amara	3.31 a	3.75 a	2.51 a	4.29 a	0.87	ns	22.00 a	33.00 a	23.67 a	45.33 a	5.83	S<0.05
I. umbellata 'Fairy'	1.78 a	1.69 a	1.50 a	1.80 a	0.28	ns	26.67 a	35.67 a	23.33 a	40.33 a	7.71	ns
L. elegans and *L.maroccana*	95.93 a	84.15 a	84.56 a	95.93 a	8.52	ns	640.7 a	773.7 a	687.7 a	845.7 a	86.09	ns
L.grandiflorum var. *rubrum*	0.61 a	0.71 a	0.29 a	0.45 a	0.11	W<0.05	13.00 ab	28.67 a	12.33 b	26.00 ab	3.58	S<0.01
L.usitatissimum	0.91 a	0.72 a	0.31 a	0.46 a	0.26	ns	8.33 a	5.67 a	4.00 a	5.00 a	1.57	ns
P.rhoeas	0.35 a	0.35 a	0.20 a	0.01 a	0.18	ns	10.33 a	5.00 a	5.00 a	1.00 a	4.26	ns
R.odorata	2.41 a	1.26 a	1.20 a	1.42 a	0.56	ns	31.67 a	19.33 a	17.33 a	23.67 a	6.11	ns
T.maritimum	1.18 a	0.80 a	0.30 a	0.70 a	0.20	W<0.05	54.33 a	49.00 a	26.33 a	63.00 a	15.48	ns
V. tricolor	0.71 a	0.63 a	0.36 a	0.43 a	0.14	ns	42.00 a	49.00 a	31.67 a	53.00 a	10.06	ns

SE=Standard Error, P=probability, W=watering regime, S=sowing rate regime, W*S=interaction between watering regime and sowing rate regime, Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

3.2 Emergence of individual species over time

The effect of sowing rate and watering on emergence every three weeks of individual species in the quadrats (30 cm x 30 cm) is shown in Table 3.2.4. The results of the first two measurements were shown only the probability from statistical analysis. In the first measurement, watering was important for emergence and as time went on, it seemed that the influence of sowing rate was greater than watering. In the first measurement, eight species were affected by watering and only one species was affected by sowing rate. In the second measurement, the species which were affected by watering decreased whereas the species which were affected by sowing increased. In the final measurement, only one species showed significant difference between the different watering regimes. There was a significant effect of interaction between watering and sowing rate in three species in final measurement. These species showed the same trend; the largest number of flowing plants was observed in the treatment of watering and low sowing rate, followed by no watering and high sowing rate, watering and high sowing rate and no watering and low sowing rate.

In the majority of species, the number of plants increased over time, but there were some exceptions. The number of *L. elegans* and *L. maroccana*, which were the highest emergence species, showed the largest number in the first measurement and decreased in the later measurements. *A. maritimum* showed the highest emergence in the second measurement. There was a tendency that the species which produced a large number of plants early on, tailed off in the later measurements.

Table 3.2.4 Mean emergence of individual species per quadrat over time (n=9)

	28th July	18thAugust	11th September					
			Watering		No watering			
	P	P	2g	4g	2g	4g	SE	P
A. arvensis	W<0.05	W<0.05	2.44 a	2.56 a	0.70 a	1.67 a	0.53	W<0.05
A. maritimum	ns	S<0.01	12.22 b	18.78 ab	12.22 b	21.67 a	1.80	S<0.01
C. cyanus	ns	S<0.05	0.78 a	1.00 a	0.89 a	1.00 a	0.35	ns
C. segetum	S<0.05	ns	1.00 a	1.56 a	0.56 a	1.67 a	0.39	S<0.05
C. tricolor	W<0.01	ns	0.44 a	0.67 a	0.56 a	0.33 a	0.29	ns
C. regalis	ns	ns	1.22 a	0.78 a	0.22 a	1.22 a	0.32	S*W<0.05
C. tinctoria	W<0.01	ns	4.00 a	3.11 a	2.22 a	3.78 a	0.65	ns
E. plantagineum 'Blue Bedder'	ns	ns	1.11 a	1.44 a	1.11 a	1.67 a	0.41	ns
E. californica	ns	ns	1.00 a	0.33 a	0.11 b	0.44 a	0.23	S*W<0.05
G. molle	ns	W<0.05	2.56 a	4.56 a	1.67 b	2.78 a	0.71	S<0.05
G. muralis	ns	S<0.01	3.44 a	6.22 a	4.11 a	5.00 a	0.78	S<0.05
I. amara	W<0.05	ns	2.44 a	3.22 a	1.11 a	3.89 a	0.78	S<0.05
I. umbellata 'Fairy'	W<0.01	ns	1.33 a	2.78 a	1.89 a	3.11 a	0.49	S<0.05
L. elegans and *L. maroccana*	ns	S<0.05	40.33 ab	45.33 ab	30.89 b	49.44 a	4.21	S<0.01
L. grandiflorum var *rubrum* and *L. usitatissimum*	ns	ns	1.33 a	2.22 a	1.56 a	2.00 a	0.43	ns
P. rhoeas	W<0.01	S<0.05	1.44 a	0.33 a	0.44 a	0.33 a	0.43	ns
R. odorata	W<0.01	W<0.01 S*W<0.05	3.22 a	1.22 a	1.67 a	2.00 a	0.59	ns
T. maritimum	W<0.01	W<0.01	4.56 a	1.67 b	1.44 b	2.44 ab	0.57	S*W<0.01
V. tricolor	ns	ns	3.00 a	1.78 a	1.67 a	1.89 a	0.36	ns

P=probability, SE=Standard Error, W=watering regime, S=sowing rate regime, W*S=interaction between watering regime and sowing rate regime, Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

3.3 Growth of individual species

The growth of individual plants (height, leaf or shoot number, diameter) is shown in Table 3.2.6. The results of the first two measurements were shown only the probability from statistical analysis. Although the majority of species did not show a significant difference in the shoot mass (Table 3.2.3), when the growth was analyzed by individual species, the growth of many species showed a significant effect of watering. In the fist two measurements, the majority of species showed a significant effect of watering, sowing rate and the interaction between them. It appears that watering was important for the early stage of establishment. Overall, there was a tendency that the plants in the treatment of the watering and low sowing rate showed the largest growth followed by watering and high sowing rate, no watering and low sowing rate and no watering and high sowing rate. In both watering and no watering regime, many species showed better growth at the low sowing rate. The growth of most species on the roof was reduced compared to their normal growth on the ground, mainly because of stress caused by shallow substrate, drought and exposure. According to Koehler (2004b), generally taller plants on the ground have smaller size on extensive green roofs. Some species, *A. aestivalis, C. tricolor, C. regalis, E. californica, G. molle, T. maritimum* and *V. tricolor* were very small in size and not prominent in this seed mixture.

The change of height of the representative individuals over time is shown in Fig.3.2.9. The height shown was the average of all treatments (n=60). At the beginning of August, the height of most of the species is less than 15 cm and there was much difference between species. However, as time went, the species could be divided into three groups; Short (shorter than 10 cm, e.g. *A. maritimum*), Medium (between 10 cm and 20 cm, e.g. *E. plantagineum* 'Blue Bedder', *Iberis* spp,) and Tall (taller than 20 cm, e.g. *C. tinctoria, G. muralis, Linaria* spp.) When the species for the annual vegetation is chosen, it is important to choose the different height of species to create more visual effect.

Table 3.2.6 Growth of individual species (n=15)

		Beginning of August	End of August	Beginning of October					
				Watering		No Watering			
		P	P	2g	4g	2g	4g	SE	P
A. arvensis	Height(cm)	W<0.01	W<0.01	4.15 a	3.11 a	1.48 a	1.84 a	0.44	W<0.01
	Leaf number	ns	ns	8.27 a	6.40 a	6.80 a	7.13 a	0.75	ns

	Diameter(cm)	W<0.01 S<0.05	W<0.01	1.47 a	1.25 a	1.09 a	1.08 a	0.11	W<0.05
A. maritimum	Height(cm)	W<0.01 S<0.05	W<0.01	6.79 a	6.27 a	6.09 a	6.02 a	0.51	ns
	Shoot number	W<0.01 S<0.01	ns	9.47 a	12.40 a	13.27 a	9.80 a	1.31	W*S <0.05
	Diameter(cm)	W<0.01 S<0.05	S<0.05	9.64 a	8.68 a	8.69 a	7.31 a	0.59	ns
C. cyanus	Height(cm)	W<0.01	W<0.01	13.19 a	18.72 a	14.17 a	13.37 a	1.73	ns
	Leaf number	W<0.01	W<0.01	8.67 b	21.93 a	14.80 ab	14.27 ab	2.53	S<0.05 W*S <0.01
	Diameter(cm)	W<0.01	W<0.05	3.71 a	6.12 a	2.86 a	3.25 a	0.89	W<0.05
C. segetum	Height(cm)	W<0.05 S<0.05 W*S <0.01	S<0.05	25.39 a	13.89 b	13.29 b	14.37 b	2.38	W<0.05 S<0.05 W*S <0.05
	Leaf number	S<0.01	S<0.05	15.20 a	11.67 a	12.00 a	11.73 a	1.27	ns
	Diameter(cm)	W<0.05 S<0.05 W*S <0.05	W*S <0.05	3.81 a	2.61 a	2.65 a	3.38 a	0.45	W*S <0.05
C. tricolor	Height(cm)	W<0.05	W<0.05	8.11 a	7.20 a	6.77 a	6.65 a	1.12	ns
	Leaf number	ns	ns	7.13 a	6.93 a	7.73 a	6.73 a	0.80	ns
	Diameter(cm)	ns	ns	2.09 a	2.12 a	2.33 a	2.30 a	0.20	ns
C. regalis	Height(cm)	ns	ns	1.53 a	0.96 a	1.56 a	0.71 a	0.38	ns
	Leaf number	ns	W<0.01	4.07 a	4.13 a	3.87 a	3.20 a	0.42	ns
	Diameter(cm)	ns	W<0.01	1.14 a	1.15 a	1.06 a	0.95 a	0.12	ns
C. tinctoria	Height(cm)	W<0.01 S<0.05 W*S <0.05	W<0.05	34.36 a	30.72 a	25.52 b	24.57 b	2.06	W<0.01
	Leaf number	S<0.05	S<0.05	7.00 a	7.00 a	5.13 b	5.87 ab	0.47	W<0.01
	Diameter(cm)	ns	ns	2.39 a	2.37 a	1.52 a	1.31 a	0.38	W<0.05
E. plantagineum 'Blue Bedder'	Height(cm)	W<0.01	W<0.01	17.32 a	14.79 b	10.98 b	12.32 ab	0.97	W<0.01
	Leaf number	ns	ns	7.47 a	2.40 b	3.40 b	3.47 b	0.82	S<0.01 W*S <0.01
	Diameter(cm)	W<0.01	S<0.05	3.67 a	2.88 a	3.50 a	3.12 a	0.52	ns
E. californica	Height(cm)	W<0.01 S<0.01 W*S <0.01	W<0.01 S<0.01 W*S <0.01	6.43 a	3.97 b	3.46 b	3.01 b	0.62	W<0.01 S<0.05
	Leaf number	W<0.05	W<0.01	5.00 a	4.73 a	4.20 a	3.60 a	0.51	ns
	Diameter(cm)	W<0.01 S<0.01 W*S <0.01	W<0.05 W*S <0.05	3.40 a	2.43 a	2.21 a	3.78 a	0.41	ns
G. molle	Height(cm)	W<0.01	W<0.01	4.26 a	3.37 b	2.59 b	2.37 b	0.33	W<0.01
	Leaf number	ns	ns	4.27 a	4.93 a	4.53 a	3.60 a	0.41	ns
	Diameter(cm)	ns	W<0.05	3.69a	3.62a	3.22 a	2.73 a	0.31	W<0.01
G. muralis	Height(cm)	ns	W<0.01	28.73 a	25.77ab	21.15b	20.79 b	1.78	W<0.01
	Leaf number	ns	ns	12.67 a	8.80 a	16.40 a	13.67 a	2.04	ns
	Diameter(cm)	W<0.01	ns	12.68 a	9.40 b	9.59 b	8.41 b	0.77	W<0.05 S<0.01
I. amara	Height(cm)	W<0.01	W<0.01 W*S <0.01	18.73 a	16.11 b	16.22 ab	15.87 b	0.69	S<0.05
	Leaf number	W<0.01	W<0.05	4.33 a	3.47 a	6.53 a	4.87 a	1.04	ns
	Diameter(cm)	ns	S<0.05	4.07 a	4.09 a	4.01 a	3.82 a	0.38	ns
I. umbellata 'Fairy'	Height(cm)	W<0.01	W<0.01	14.99 a	11.71 b	9.63 b	10.93 b	0.76	W<0.01 W*S <0.01
	Leaf number	W<0.01	ns	0.53 a	0.87 a	2.80 a	2.67 a	0.95	W<0.05
	Diameter(cm)	ns	W<0.05	3.36 a	2.16 a	2.70 a	2.42 a	0.39	ns
L. elegans	Height(cm)	W<0.01 S<0.05	ns	40.30 a	34.37 a	37.59 a	37.20 a	2.65	ns
	Shoot number	ns	ns	3.80 a	2.93 a	4.33 a	3.20 a	0.49	S<0.05
	Diameter(cm)	ns	S<0.05	3.79 a	2.96 a	3.79 a	3.38 a	0.42	ns
L. maroccana	Height(cm)	W<0.01	W<0.05	27.12 a	26.93 a	27.05 a	28.31 a	2.05	ns
	Shoot number	S<0.05 W*S <0.05	S<0.05	2.47 a	2.60 a	2.13 a	2.80 a	0.33	ns

	Diameter(cm)	ns	ns	1.94 a	2.14 a	2.50 a	2.96 a	0.30	W<0.05
L. grandiflorum var rubrum	Height(cm)	W<0.01 S<0.01	W<0.01 S<0.05	26.81 a	26.21 a	18.69 a	16.50 a	1.623	W<0.01
	Leaf number	ns	W<0.05	8.93 b	11.73 ab	11.33 ab	13.87 a	0.94	W<0.05 S<0.01
	Diameter(cm)	W<0.05	S<0.05	0.80 ab	0.76 ab	1.08 a	0.66 b	0.10	S<0.05
L. usitatissimum	Height(cm)	W<0.01	W<0.01	22.15 a	21.53 a	14.97 b	15.65 b	0.82	W<0.01
	Leaf number	W<0.01	ns	6.47 a	7.40 a	9.13 a	9.20 a	1.30	ns
	Diameter(cm)	ns	W<0.01	1.65 a	0.96 b	0.91 b	0.97 b	0.15	W<0.05 S<0.05 W*S <0.05
P. rhoeas	Height(cm)	W<0.01	W<0.01	15.52 a	16.43 a	12.57 ab	6.49 b	1.91	W<0.01
	Leaf number	W<0.01 S<0.05	S<0.01	4.27 a	4.47 a	3.60 a	2.93 a	0.55	ns
	Diameter(cm)	W<0.01 S<0.05	W<0.05	0.93 a	1.02 a	1.19 a	0.60 a	0.24	ns
R. odorata	Height(cm)	W<0.01	W<0.05	10.53 a	8.96 a	8.72 a	7.03 a	1.42	ns
	Leaf number	ns	ns	9.87 a	13.40 a	23.07 a	11.67 a	3.67	W*S <0.05
	Diameter(cm)	ns	ns	2.83 a	2.61 a	3.09 a	2.40 a	0.36	ns
T. maritimum	Height(cm)	W<0.01	W<0.01	11.68 a	7.10 a	3.88 b	3.54 b	1.16	W<0.01 S<0.05
	Shoot number	W<0.05	W<0.05	9.80 a	8.00 ab	6.93 b	6.13 b	0.61	W<0.01 S<0.05
	Diameter(cm)	W<0.01	W<0.01	2.16 a	2.00 a	1.69 a	1.82 a	0.21	ns
V. tricolor	Height(cm)	W<0.05	ns	1.63 a	1.79 a	1.65 a	0.99 a	0.40	ns
	Leaf number	ns	ns	6.00 a	6.73 a	6.53 a	6.00 a	0.62	ns
	Diameter(cm)	W<0.01	W<0.05	1.79 a	2.01 a	1.89 a	1.56 a	0.22	ns

P=probability, SE=Standard Error,W=watering regime, S=sowing rate regime, W*S=interaction between watering regime and sowing rate regime, Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

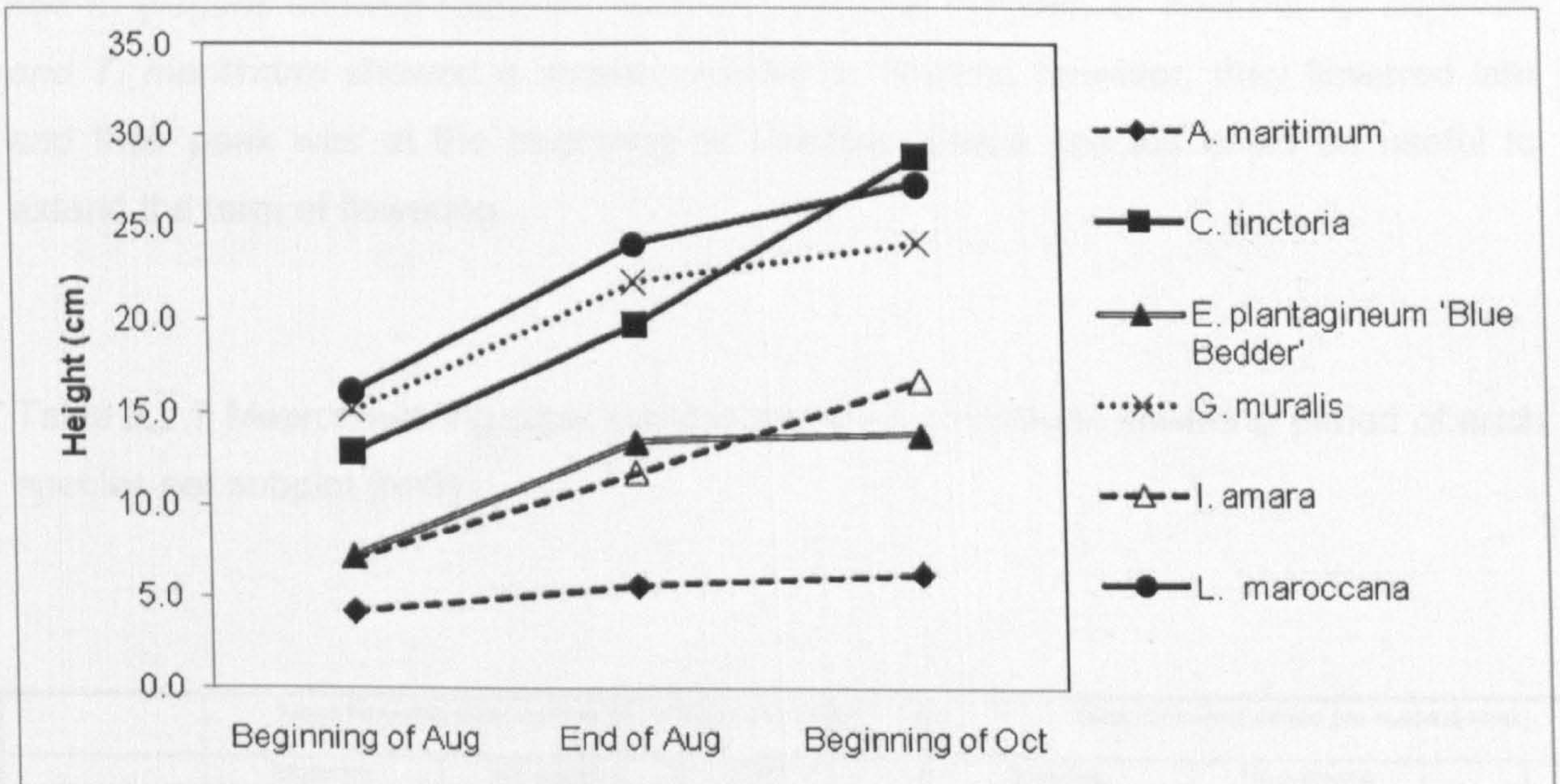


Fig.3.2.9 Change of height of the representative individuals over time

3.4 Flowering performance of individual species

Flowering performance of the individual species per subplot is shown in Table 3.2.7. The flowering period was evaluated by counting the weeks between which they start flowering until they finish. Again, for the majority of species, there was no significant effect of watering and sowing rate and the interaction between these treatments on the mean number of flowering plants and mean flowering period. Watering is important for flower performance of some plant species. Mean number of flowering plants of *A. arvensis, L. usitatissimum* and *T. maritimum* were significantly affected by watering, however, the number of flowering plants of these species was small. Only in *A. maritimum*, there was a significant effect of sowing rate. *A. maritimum, L. elegans*, and *L. maroccana* had large numbers of flowering every week. *E. californica* and *G. molle* had no flower in any treatments. *C. regalis* had only one flower for a few days and this flower had already disappeared by the time of the weekly measurement. For the mean flowering period, *C. cyanus, L. usitatissimum* and *T. maritimum* were significantly affected by watering and *C. tinctoria* were affected by the interaction between watering and sowing rate. *A. maritimum, E. plantagineum* 'Blue Bedder', *G. muralis, I. amara, I. umbellata* 'Fairy', *L. elegans,* and *L. maroccana* showed a long flowering period. A summary of flowering number per subplot over time is shown Fig.3.2.10 (Large number) and Fig. 3.2.11 (Small number). The flowering number shown per subplot was the average of all treatments. *A. maritimum* and *L. maroccana* showed a particularly large number of flowers and their peak was the middle of August and beginning of September. *E. plantagineum* 'Blue Bedder', *G. muralis, I. amara, I. umbellata* 'Fairy' and *L. elegans* showed relatively constant flowering number. *C. tinctoria, C. segetum and T. maritimum* showed a smaller number of flowers, however, they flowered late and their peak was at the beginning of October. These species could be useful to extend the term of flowering.

Table 3.2.7 Mean flowering plant number per week and mean flowering period of each species per subplot (n=3)

	Mean flowering plant number per subplot per week						Mean flowering period per subplot(week)					
	Watering		No watering				Watering		No watering			
	2g	4g	2g	4g	SE	P	2g	4g	2g	4g	SE	P
A. arvensis	0.26 a	0.10 a	0 a	0.08 a	0.06	W<0.05	2.00 a	1.00 a	0 a	1.00 a	0.65	ns
A. maritimum	74.87a a	108.00 a	70.21 a	98.54 a	8.62	S<0.01	12.67 a	12.67 a	13.00 a	12.67 a	0.29	ns
C. cyanus	1.00 a	1.92 a	0.46 a	1.36 a	0.44	ns	7.67 a	9.67 a	4.67 a	6.33 a	1.20	W<0.05
C. segetum	1.18 a	1.28 a	0.79 a	0.87 a	0.35	ns	5.33 a	5.00 a	5.33 a	3.33 a	0.71	ns
C. tricolor	0.03 a	0.05 a	0.05 a	0.03 a	0.03	ns	0.33 a	0.67 a	0.67 a	0.33 a	0.44	ns
C. regalis	0 a	0 a	0 a	0 a	-	ns	0 a	0 a	0 a	0 a	-	ns
C. tinctoria	1.36 a	1.41 a	0.87 a	0.69 a	0.37	ns	4.00 a	5.33 a	5.00 a	2.67 a	0.62	W*S<0.05

E. plantagineum 'Blue Bedder'	3.15 a	3.46 a	2.69 a	3.26 a	0.73	ns	10.33 a	10.33 a	11.00 a	9.67 a	0.91	ns
E. californica	0 a	0 a	0 a	0 a	-	ns	0 a	0 a	0 a	0 a	-	ns
G. molle	0 a	0 a	0 a	0 a	-	ns	0 a	0 a	0 a	0 a	-	ns
G. muralis	7.85 a	9.36 a	9.26 a	9.36 a	1.41	ns	10.33 a	11.00 a	12.00 a	10.33 a	0.55	ns
I. amara	8.62 a	12.62 a	7.31 a	17.6 a	3.46	ns	10.33 a	10.33 a	10.00 a	9.67 a	0.29	ns
I. umbellata 'Fairy'	5.03 a	6.23 a	5.62 a	7.10 a	1.30	ns	9.33 a	10.33 a	10.33 a	9.67 a	0.60	ns
L. elegans	15.97 a	14.33 a	14.64 a	15.56 a	2.07	ns	9.00 a	9.33 a	9.00 a	9.00 a	0.17	ns
L. maroccana	57.18 a	56.62 a	47.15 a	51.85 a	6.02	ns	11.00 a	11.00 a	10.67 a	11.00 a	0.17	ns
L. grandiflorum var rubrum	0.51 a	0.33 a	0.38 a	0.31 a	0.09	ns	4.33 a	3.33 a	4.00 a	3.33 a	0.82	ns
L. usitatissimum	0.15 a	0.28 a	0 a	0.05 a	0.08	W<0.05	1.67 a	2.33 a	0 a	0.67 a	0.58	W<0.05
P. rhoeas	0.62 a	0.38 a	0.18 a	0.08 a	0.26	ns	3.33 a	2.33 a	1.67 a	1.00 a	1.19	ns
R. odorata	0.69 a	0.49 a	0.51 a	0.31 a	0.15	ns	5.67 a	5.67 a	5.67 a	3.67 a	1.42	ns
T. maritimum	1.82 a	0.79 ab	0.28 b	0.23 b	0.25	W<0.01	6.00 a	5.33 a	2.00 a	1.67 a	0.99	W<0.01
V. tricolor	0.05 a	0.05 a	0.05 a	0 a	0.04	ns	0.33 a	0.67 a	0.67 a	0 a	0.41	ns

W=watering regime, S=sowing rate regime, W*S=interaction between watering regime and sowing rate regime, SE=Standard Error, Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

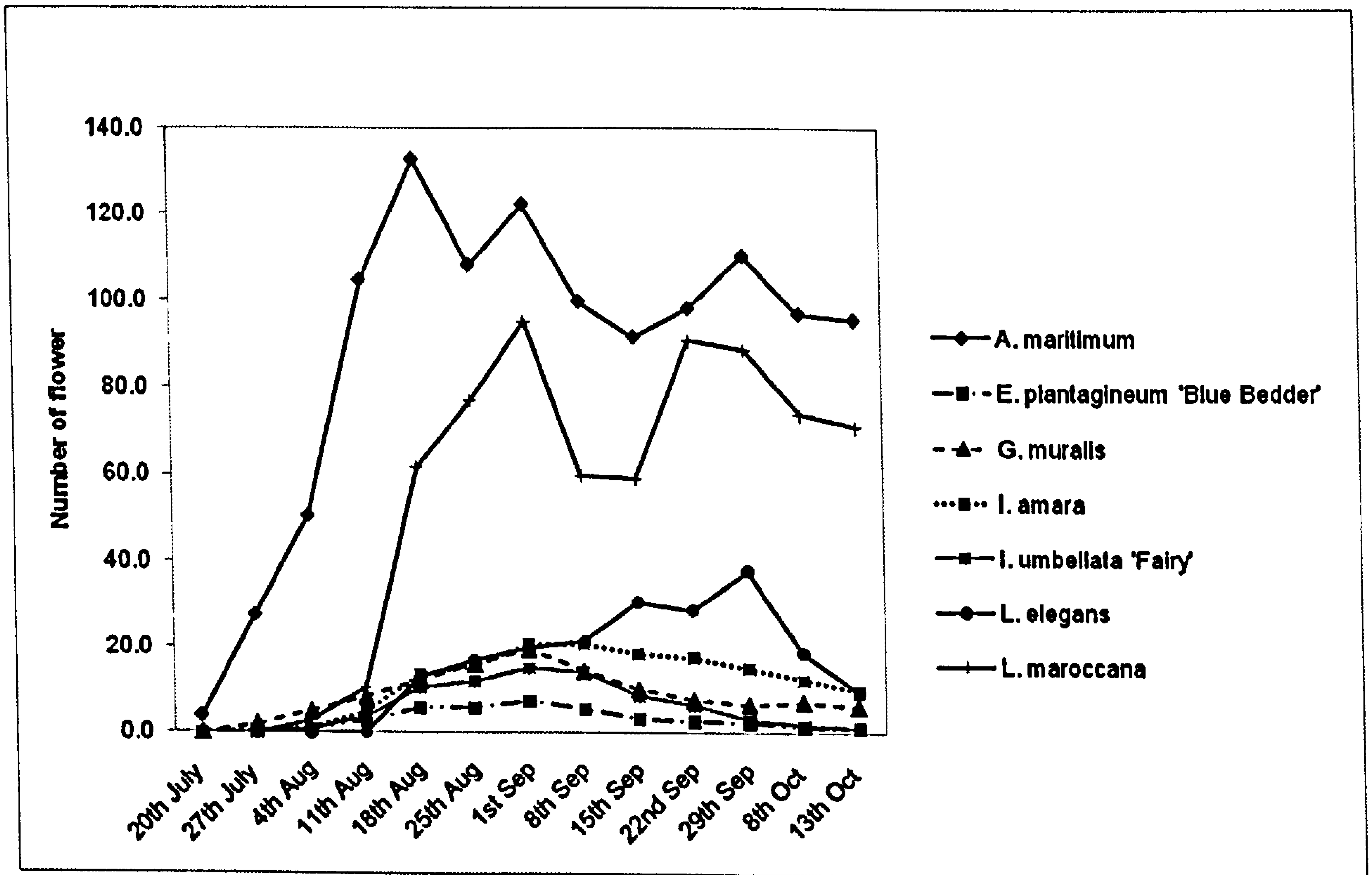


Fig.3.2.10 Summary of flowering number per subplot over time (1) (Large number)

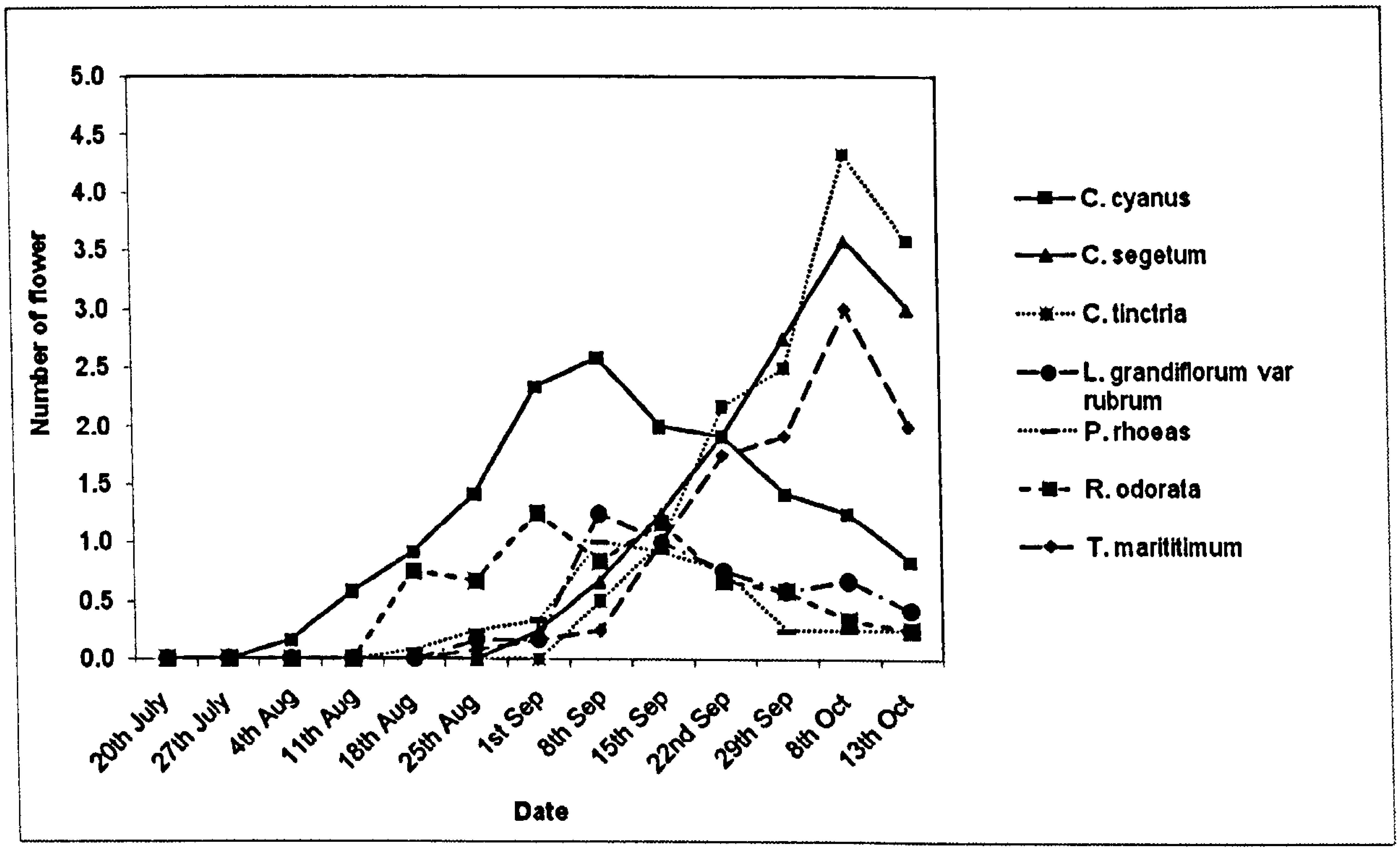


Fig.3.2.11 Summary of flowering number per subplot over time (2) (Small number)

3.5 Summary of performance of individual species

To make clear the potential of individual species of annuals in mixture, emergence, plant size, flowering number and length of flowering are summarized in Table 3.2.8. For successful annual plant seed mixture, it is necessary to choose the plants which have high emergence, good growth, high number of flowering plants and long flowering term. In this study, *A. maritimum, C. tinctoria, E. plantagineum* 'Blue Bedder',*G. muralis, I. amara, I. umbellata* 'Fairy', *L. elegans* and *L. maroccana* fulfilled these requirements. In the central UK, these species are recommended for use mixture on extensive green roofs with substrate depths similar to those used in this experiment. On the contrary, *A. aestivalis, A. arvensis, C. regalis, E. californica, G. molle* and *V. tricolor* were not successful in this study.

Table 3.2.8 Summary of performance of individual species

	Emergence	Growth	Height	Number of flowering plants	Length of flowering term	Potential for annual mixture
A. aestivalis	No	No	No	No	No	
A. arvensis	High	Small	Short	Small	Short	
A. maritimum	High		Short	Large	Long	High
C. cyanus	Low		Medium	Small	Medium	
C. segetum	Low		Medium	Small	Medium	
C. tricolor	Low		Low	Small	Short	
C. regalis	Low	Small	Low	No	No	
C. tinctoria	High		Tall	Small	Short	High
E. plantagineum 'Blue Bedder'	Low		Medium	Small	Long	High
E. californica	Low	Small	Short	No	No	
G. molle	High	Small	Short	No	No	

G. muralis	High		Tall	Medium	Long	High
I. amara	Medium		Medium	Large	Long	High
I. umbellata 'Fairy'	Medium		Medium	Large	Long	High
L. elegans	High		Tall	Large	Long	High
L. maroccana	High		Tall	Large	Long	High
L. grandiflorum var rubrum	Medium		Tall	Small	Short	
L. usitatissimum	Low		Medium	Small	Short	
P. rhoeas	Low	Small	Medium	Small	Short	
R. odorata	Medium		Short	Small	Medium	
T. maritimum	High		Short	Small	Short	
V. tricolor	High	Small	Short	Small	Short	

Emergence: Mean plant number per subplot when they were harvested, No emergence=0, 0≤Low≤20, 20<Medium≤50, 50<High
Growth: No growth=No emergence, S=small size and inconspicuous
Height: No height=No emergence, 0<Short≤10 cm, 10 cm<Medium≤20 cm, 20 cm<Tall
Number of flowering plants: Mean flowering number per week per subplot, No flower=0 0<Small≤5, 5<Medium≤11, 11<Large
Length of flowering term: No flower=0, 0≤Short≤5 weeks, 5 weeks <Medium≤9 weeks, 9 weeks <Long

3.6 Overview of annual plant growth

Overview of annual plants growth over time under the different watering regime and sowing rate is shown in Table 3.2.5. Same tendency was observed in individual treatment, therefore, the change of representative subplot (Plot 2 for watering regime and Plot 3 for no watering regime) is shown. At the beginning, the plant growth of no watering regime was limited although some of *A. maritimum* had flowers. In the middle of August, the plants in the no watering regime started to grow. In the no watering regime, the majority was creeping plants such *A. maritimum* whereas tall plants such as *L. maroccana* was dominance in the watering regime. When they have enough watering, there is not much difference between low sowing rate and high sowing rate, although variety of plants was observed and individual plant growth was better in the low sowing rate. On the contrary, a higher percentage of bare ground was observed in the low sowing rate than in the high sowing rate in the no watering regime. Therefore, a high sowing rate is recommended for dry environment to have sufficient plant number to cover the ground. Some species were still flowering until middle of October, although many plants started to die down.

Table 3.2.5 Overview of annual plants growth over time under the different watering regime and sowing rate

11th August			
Watering		**No watering**	
2g/m^2	**4g/m^2**	**2g/m^2**	**4g/m^2**

21st August

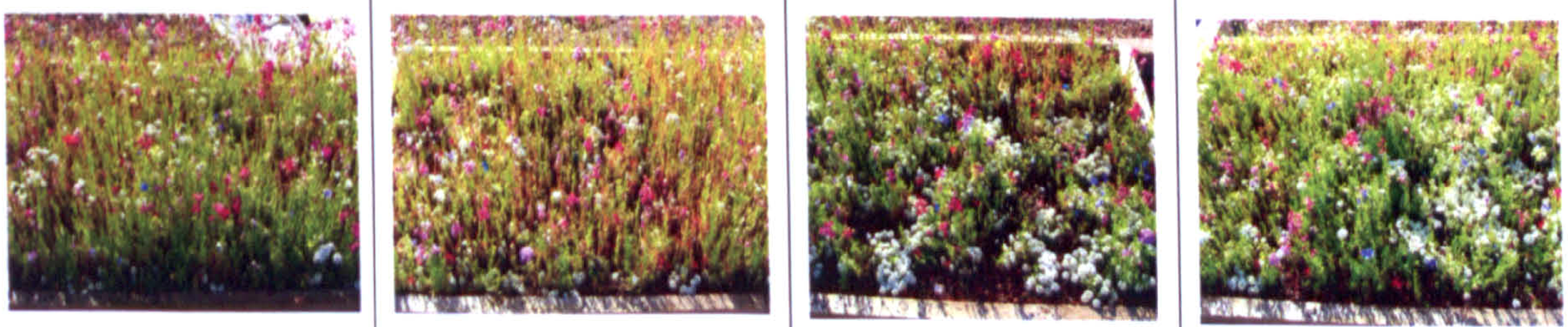
Watering		No watering	
2g/m^2	4g/m^2	2g/m^2	4g/m^2

1st September

Watering		No watering	
2g/m^2	4g/m^2	2g/m^2	4g/m^2

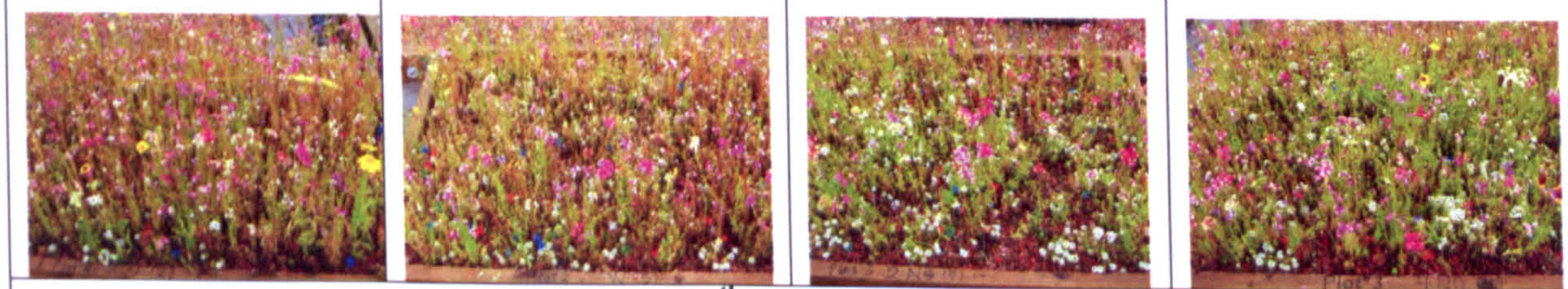
8th September

Watering		No watering	
2g/m^2	4g/m^2	2g/m^2	4g/m^2



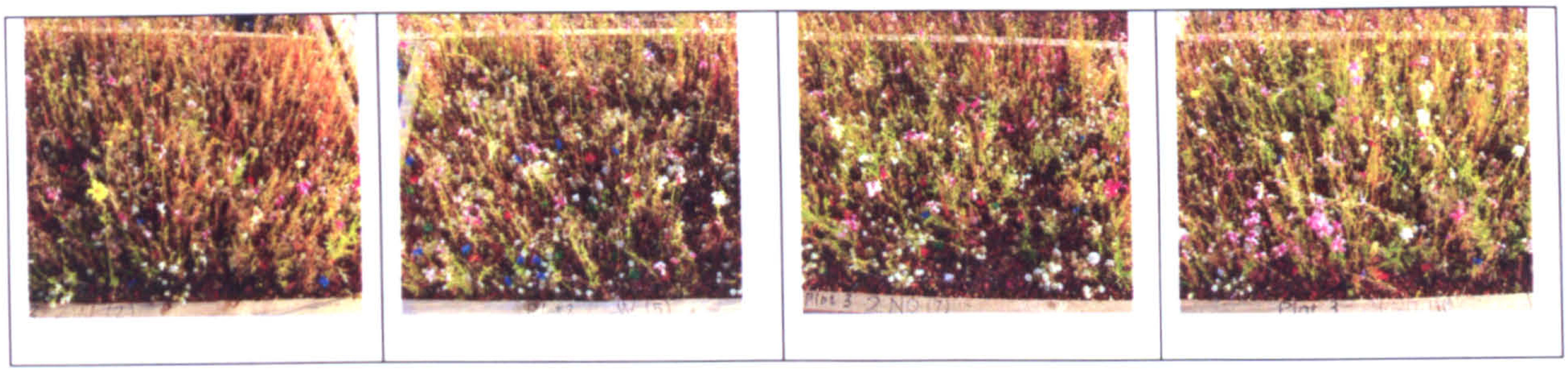
29th September

Watering		No watering	
2g/m^2	4g/m^2	2g/m^2	4g/m^2



13th October

Watering		No watering	
2g/m^2	4g/m^2	2g/m^2	4g/m^2



4. Discussion

4.1 Effect of supplemental watering

Generally, it is believed that irrigation is an important factor for greater seedling establishment and improved flower display for wildflowers (Rutledge and Holloway,1994, Goldberg,et al., 2001,Rivas-Arancibia et al., 2006). In this study, same tendency was observed. Final total shoot dry weight and total plant number were greater for watered plants, although the difference was not significant (Fig.3.2.7 and Fig.3.2.8). Also, in individual species, a few species were affected by watering in the final measurement of dry shoot weight and plant number (Table 3.2.3). Watering had a significant effect on the emergence of many species in the early stage. Probably this result would be related to the moisture in the substrate. As shown in Fig.3.2.4, until the middle of August, the watering regime was implemented every week. Hence, there was a significant difference between watering regime and no-watering regime in the moisture content of the substrate. After middle of August, the plants in both treatments had enough rainfall and they both showed high moisture content in the soil and there was no significant difference between them. These results suggest that the annuals can wait as seeds or as small plants when it is dry until they can get the enough watering and then they can start to grow quickly as soon as they receive rain. According to Went (1949), it was observed that heavy initial artificial rain caused 3 to 4 times as many annual seeds to germinate as germinated without the benefit of that rain. He concluded that any one rain might bring out only a small fraction of all possible seedlings. Other research also showed that mass germination in deserts occurs only after a threshold amount of precipitation (effective-rain) had fallen, provided that other limitation factors (mainly temperature) allowed germination. A smaller amount of rainfall resulted in scattered germination (Kigel, 1995). In current experiment, flower performance showed a similar pattern to germination. In the watering regime, a larger number of plants were in flower each week and the flowering period was also longer flowering, however, many species were not significantly affected.

From these results, it was concluded that an annual seed mixture could perform well without irrigation in the central UK if there is appropriate rain. However, in this experiment, the plants may not have experienced a severe drought. For example, previous research in the green house using annual plant species from arid regions of Western Australia, *Helichrysum cassinianum* and *Helipterum craspedioides* and *Aristida contorta*, indicated that high stress reduced plant dry weight, numbers of flowers and seeds and the ability of seeds to germinate (Mott and McComb, 1975). Therefore, if they have a dry and hot summer, supplemental irrigation may be beneficial for better germination, growth and flower performance.

4.2 Effect of sowing rate

Final total plant number was significantly higher at high sowing rate than at low sowing rate, and the sowing rate was more important for the plant number at the later stage (Table 3.2.4). However it is worth pointing out that this result may be affected not only by sowing rate but also by the larger amount of rainfall in the latter half of experimental term. The effects of seed density on germination have been reported in several studies. Inouye (1980) demonstrated that the presence of seedlings at high densities inhibits subsequent germination of desert annuals because of competition mainly by seedlings. Shaw and Antonovics (1986) and Hitchmough et al. (2004) found the liner relationship between seed rate and number of seedlings. Linhart (1976) explained that the seeds in groups enhance one another's germination because groups retain moisture better and germinating seeds releases a variety of compounds which increase the germination rates of other seed. Higher sowing rate may be recommended for potential weedy place as sowing rate increases, weed cover and density tends to drop rapidly (Stevenson et al., 1995). However, the weeds may be not serious problems in extensive green roofs because of shallow substrate and exposure on the rooftop environment.

At high sowing rate (4 g/ m^2), a larger number of seedlings emerged in the no watering regime compared with the watering regime, although there was no significant difference between the two (Fig.3.2.8). Again, this may be explained by competition between plants. The shoot biomass in the watering regime was greater than those in the no watering regime. On the contrary, the more seed lings could grow in the no watering regime since most of the plants were still small and suffered less competition. Previous research using *Salvia lyrata* (herbaceous perennial) seedlings showed similar results; the presence of adults reduced seedling emergence and the removal of adults created physically favourable sites, possibly by exposure of bare ground (Shaw and Antonovics, 1986).

In this study, shoot biomass was smaller in the higher sowing rate when they were harvested, although the difference was not significant. Similar results were reported by in previous research. Inouya et al. (1980) suggested that competition among annual plants reduced growth rate, biomass and fecundity. Goldberg et al. (2001) also concluded that at the establishment stage, exploitation competition appeared to be primary mechanism of interaction influencing growth in the annual community. From these results, it was concluded that low sowing rate (2 g/ m^2) could be better than high sowing rate (4 g/ m^2) when they have enough rain because individual plant species had better growth in low sowing rate. On the contrary, a high sowing rate is recommended for dry environment to have sufficient plant number. In the no watering regime, the germination rate was low in low sowing rate and the individual growth was not encouraged because of lack of water, therefore, a higher percentage of bare ground was observed. According to the overview of annual plant growth over time, the visual quality of the subplot in the high sowing rate was better than the low sowing rate because of larger number of plants therefore more flowering plants. In many cases, irrigation is difficult for green roofs and it is easier to have a high sowing rate rather than having supplemental irrigation for attractive plant meadows.

For flowering performance, there was the tendency that the mean number of flowering plants per subplot per week was larger at high sowing rate, probably because of higher plant number at high sowing rate (Table 3.2.7). There was not a significant effect in most species, however, the exception was *A. maritimum.* At higher density, large numbers of low-growing *A. maritimum* coexisted with other species probably because taller plants of *Linaria* spp, for example, produced the less shoot biomass and had slender growth. However, it seems that watering is a more important factor than sowing rate in flowering performance, and many species showed their best performance in the watering regime.

4.3 Individual species performance

A. maritimum, C. tinctoria, E. plantagineum 'Blue Bedder', *G. muralis, I. amara, I. umbellata* 'Fairy', *L. elegans* and *L. maroccana* were successful in this plant mixture because of their high emergence, good growth, high number of flowering plants and long flowering term (Table 3.2.8). Particularly, *A. maritimum* and *Linaria* spp. formed the backbone of the annual plant mixture. A diverse plant community provides dynamic visual interest with different structures and phenologies, and creates more habitats for biodiversity and storm water mitigation (Vitousek and Hooper, 1994; Dunnett and Kingsbury, 2004a). In this study, the same weight of seeds was used from each species. *Linaria* spp. have a smaller size of seeds than other species (Table 3.2.1), therefore, more seeds were contained in the seed mixture. *A. maritimum* is a low growing, creeping plant and is useful for filling gaps. This species was self-seedling and germination was observed just after they finished flowering in autumn. *Linaria* spp. is a slender plant and *L. maroccana* produced a different colour mixture of flowers of white, yellow, pink and orange. According to the public opinion survey of wildflower mixtures, generally, a long bloom season and the multi-coloured flowers were important (Rutledge and Holloway, 1994). This species could be priority for annual seed mixture. *G. muralis* also had a slender figure, however this species has a big flower head and the stems were broken after a strong wind. *C. tinctoria* flowered at a later time and could be used to extend the flowering season of a mix. *E. plantagineum* 'Blue Bedder', *I. amara, I. umbellata* 'Fairy' produced long flowering and have outstanding flowering attributes. *Gypsophila* spp. and *Iberis* spp. were successful in previous study in annual seed mixture for extensive green roofs (Kicher, 2004). Generally, some species, such as *C. cyanus* and *C. segetum* provide a display over several months on the ground (Dunnett 2004c), however, their flowering term was not as long as ground on the roof. Of the 22 species, only *A. aestivalis* did not germinate at all. This may be a result not only of dormancy or a low germination rate, but also the low number of seeds that was contained in the seed mixture because of its bigger seed size. The growth of *A. arvensis, C. regalis, E. californica, G. molle, P. rhoeas* and *V. tricolor* was restricted and inconspicuous and some of them did not have flowers, if any, it was very small number and short time. The reason of these species failure would probably be because of competition with other species or their failure to adapt to the green roof environment. Petals of *E. californica* and *P. rhoeas* were easily broken off on the roof environment because of strong winds. Plant selection for species which can tolerate for strong wind is an important consideration for extensive green roofs. When only annual species are used in cold climate areas, the flowering time would be shorter and after flowering, they become unsightly. Therefore, covering plants such as *Sedum* spp. may be recommended, although further study of competition between annual species and *Sedum* spp. is required.

5. Conclusion

It was confirmed that the annual seed mixtures used in this experiment are suitable for extensive green roofs because they have been shown to be easy to install, cheap and quick to establish (they started flower after one month of sowing), and the plant species were mainly drought tolerant and long flowering (more than 4 months). A successful annual plant community from seeds would be related to the appropriate sowing rate, watering management and plant selection. Watering was important for emergence and early growth. Supplemental watering improved some species growth and flowering performance, however, most of the species were not affected by watering in later stage. This might be related to the high rainfall in the latter half of experiment. A low sowing rate could be better than a high sowing rate to reduce competition among sown species and result in good individual plant growth when they have enough watering. On the contrary, a high sowing rate is recommended for dry environment to have sufficient plant number. Successful species, which showed a high germination rate, good growth and long flowering performance in this first growing season included *A. maritimum, C. tinctoria, G. muralis, I. amara, I. umbellata* 'Fairy', *L. elegans* and *L. maroccana.* Least successful species were *A. aestivalis, A. arvensis, C. regalis, E. californica, G. molle* and *V. tricolor.* The observation of this annual mixture over years might be necessary to identify individual species growth and further germination and self-seeding. There is the possibility that species which were not successful in the first growing season will be better in the following year and also the other way around. In addition, it is recommended to grow individual species by themselves as well as in mixture to test their suitability for the roof environment.

3-3 Extensive green roofs using geophytes in the UK: Effect of substrate depth and covering plants

Abstract
Geophytes (bulbs, corms and tubers) have great potential for use on extensive and semi-extensive green roofs. Many small or low growing geophyte species, such as *Tulipa* spp., are found naturally in desert regions growing in arid stony or rocky habitats, where they flower in the spring and die back underground to survive the hostile hot and dry summer period as dormant geophytes. The parallels with the green roof context are clear. Moreover, geophytes can provide bright colour, visual interest and nectar sources at a time of year when little else may be flowering on a green roof. However, their use has not been widely recognized and there is as yet little information about geophyte species selection, their survival rate, flowering time, and performance on a roof. Two experiments were carried out on the performance of geophytes using 26 species of geophytes for Experiment 1 (over two growing seasons 2005-2006) and 18 species for Experiment 2 (one growing season 2006). The geophytes were grown at two depths (5cm and 10cm for Experiment 1, 8cm and 17cm for Experiment 2) of a commercial green roof substrate composed of crushed recycled brick and 10% organic matter. To investigate the susceptibility of geophytes to competition with a covering of permanent plants, geophytes were grown with and without a surface vegetation layer of *Sedum album*. Overall, growth, survival rate, regeneration and flowering of geophytes were more successful in the deep substrate than the shallow substrate, probably due to the advantage of moisture retention, reduced temperature fluctuation and protection from digging by animals. Although the statistical analysis did not show significant differences, the vegetation cover by *Sedum* seemed to work as a protection layer for geophytes and their overall emergence was encouraged with *Sedum*, especially in the shallow substrate. About half the species showed better growth, flowering and regeneration with *Sedum* spp. *Iris bucharica, Muscari azureum, Tulipa clusiana* var. *chrysantha, T. humilis, Narcissus cyclamineus* 'February gold', *T. polychroma, T. tarda, T. turkestanica* and *T. urumiensis* have potential for extensive green roofs. Particularly, *Iris bucharica, Muscari azureum, T. clusiana* var. *chrysantha* and *T. humilis* showed good performance at a depth of 5cm as well. Unsuccessful species, which showed low emergence, insufficient growth or no flowering, were *Allium cernuum, A. karataviense* 'Ivory queen', *A. ostrowskianum, Crocus sieberi* 'Tricolor', *C. tommasinianus, C. vernus* 'Vanguard', *Iris danfordiae, Ixia* 'Mixture', *Sparaxis tricolor, T. bakeri* 'Lilac wonder', *T. hageri* 'Splendens' and *T. kolpakowskiana.* It is concluded that geophytes can be used to create greater seasonal interest and aesthetic quality of extensive green roofs.

Finally, because of the various difficult experiences in the use of the roof of commercial building for this experiment, when the experiment site for green roofs is chosen, all possible limitations should be carefully considered to achieve the good quality of research.

1. Introduction

1.1 Definition of geophytes

'Geophytes' are plants with a swollen storage organ: true bulbs, corms, tubers and rhizomes (Mathew and Swindells, 1994). Bulbs (e.g. Daffodils, Tulips and Lilies) have swollen stems and their fleshy scales grow up from basal plates and contain next season's flowers and leaves in an embryo. Corms (e.g. Crocus, Colchicum and Gladioli) also have swollen stems in which nutrients are stored, but are of solid construction. Tubers (e.g. Begonia, Anemones and Cyclamens) and rhizomes (e.g. Irises) have swollen roots (Blamey and Blamey,1979, Mathew and Swindells, 1994). Although the structures are different, these plants act the same way; the structures all act as storage organs and allow plants to retreat underground for long periods of dormancy (Garret and Dusoir, 2004). In this chapter, the term 'geophyte' is used in a general way to describe any plant with a swollen storage organ.

1.2 Characteristics of geophytes

It is to be expected that many geophytes are well adapted for the harsh green roof environment. They often come from dry climates; South Africa, the Mediterranean basin and Central Asia (Kingsbury, 1996), where the winters are wet and summers are hot and dry, with a short spring (Phillips and Rix, 1989). These plants can grow, flower and seed during cool moist seasons and then disappear into the comparative cool of the earth when the sun bakes the land in the summer (Kingsbury, 1996). The growing season is short, and the plants need the stored energy to flower and set seed quickly in the spring (Blamey and Blamey,1979). In dormancy, geophytes show no apparent external morphological changes or growth, but internally, many physiological and morphological events occur, such as flower differentiation or root initiation (Le Nard 1983, Le Nard and De Hertogh 1993). In the autumn, root growth occurs when soil water again becomes available (Rees, 1972), however, geophytes such as Lilies and Tulips are dormant in the winter and dormancy is broken by a period of several weeks at low temperature (approximately 4°C) (Langens-Gerrits et al. 2003). This is also a strategy to reduce the impact of competition. For example, in grasslands, when grass and other strong-growing meadow plants are vigorous in the summer, geophytes plants go into summer dormancy (Phillips and Rix, 1989, Garret and Dusoir, 2004). A deep, subterranean bud is advantageous in arctic and alpine habitats, preventing freezing (Raunkiaer, 1934). Many geophytes are hardy and they will survive temperatures as low as they will encounter in the UK (Rees, 1992). Moreover, geophytes may be able to provide additional benefits and are summarized below.

- They grow and flower in a short period after planting
- Flowering is earlier than many other herbaceous perennials
- They provide a wide range of colours and forms as well as nectar sources
- The storage organs often act as a means of propagation (vegetative reproduction)
- Little supplemental watering is required
- Initial cost is relatively high but subsequent costs are low

1.3 Competition with covering plants

On the contrary, there are disadvantages: flowering times of individual plants are relatively short and, after flowering, they become unsightly or even die down. In addition, potential geophyte species for extensive green roofs tend to be winter to early summer growing. Hence, it has been recommended that they are combined with plants that cover the ground throughout the year. In choosing covering plants for geophytes, care is needed to avoid very vigorous plants which root down as they spread sideways, as many geophytes resent excessive root competition, it is better to use the many suitable low growing plants which cover quite a large area in the course of a growing season and then die back to a central rootstock during the winter (Elliott, 1995). Geophyte species can be combined with grasses which is the simplest system of growing, requiring minimum maintenance and giving continuous flowering over many years (Rees, 1992). However, this method of growing is suitable for only some species (Narcissus, Galanthus). There have been some studies of the competition between the growth of geophytes and covering plants or weeds. Hughes (1986) investigated the selection of low biomass turf species that do not become excessively rank during the winter growing season of many geophytes. In this study, the most successful turf was *Festuca rubra* var. *commutata*. However, even with grass species such as these, geophytes with a mature foliage height of less than 20cm are unlikely to be successful where the mild winters permits substantial grass growth during this period. It should be remembered that the geophytes which have potential for green roofs tend to be dwarf and covering plants should be even shorter than this. In another study, it was shown that competition intensity between *Allium vineale* and *Lolium perenne* affected *A. vineale* 's emergence and growth (Strong competition: *Allium* was planted into an already established *Lolium*, Medium competition: *Allium* was planted together with seeds of *Lolium*, Weak competition: *Lolium* seeds was sown later, No *Lolium*: No competition). The greater the severity of *Lolium* competition, the greater was the reduction of leaf number and length, and the width of the Allium plants. It was also observed that the shorter the growing season, the earlier die-back of *Allium* (Lazenby, 1961b). When an *Allium* species was grown with annual weeds (*Polygonum aviculare, Stellaria media, Poa annua, Fumaria officinalis*), dry weight and size of the geophytes were decreased. This is because the weeds emerged earlier than *Allium* and their growth rates were greater than those of geophytes, therefore, this caused the nutrient removal and later moisture stress (Hewson and Roberts, 1973). It is important to choose the covering plant species and their planting season so that the geophytes do not have too much competition.

1.4 Geophytes for green roofs

Dwarf geophytes, whose habitats are hot and dry during the summer such as *Tulipa humilis*, might be appropriate for extensive green roofs. Generally, they are more drought tolerant than large hybrids because they have a sturdier tunic, sometimes lined with hairs that plugs the neck opening and protects the geophyte from drying out in the arid summers such as on the steppes of Central Asia (Glattstein, 2005). Short species may be able to withstand wind on green roofs, since tall or top-heavy flowers will not stand up to a windy site (Rees, 1992). Also, the sizes of the storage organs of dwarf geophytes are small, so they can tolerate a shallow planting and it is therefore to be expected that they are well adapted for thin substrates. Good drainage, shelter from cold winds, and summer ripening all play an important part in maintaining the health and survival of Mediterranean geophytes grown in the UK climate (Garrett and Dusoir, 2004). These conditions can be seen as analogous with green roof environments.

The most commonly encountered geophytic genus on extensive green roofs is Allium, of which, *A. pulchellum*, *A. schoenoprasum*, *A. flavum* are particularly valuable (Dunnett and Kingsbury, 2004a). According to long-term research on extensive green roofs in Berlin, *A. schoenoprasum* was the most dominant plant species over 20 years. It did not start growing on the roofs until some years after the construction, however, it developed to more than 75% coverage because of self-seeding (Koehler, 2006). Another potential geophyte genus for green roofs could be dwarf species of *Tulips, Daffodils, Muscari* and *Crocus* (Snodgrass and Snodgrass, 2006). It was observed by the author that *M. armeniacum* is present and increasing after appearing spontaneously on a 27 years old extensive grass roof in the UK. *Lilium auratum* has been used for thatched roofs traditionally in Japan for the purpose of reinforcement and aesthetics. These plant species also have potential since they are well adapted for thin substrate.

1.5 Performance of geophyte at different substrate depth

Little previous research on geophyte growth at different depths appears to have been done. However, there have been some studies of depth and geophyte growth in nature. There are several ways in which variations in geophyte depth could significantly affect geophyte performance: the position of the geophytes determines the depth of the substrate through which the developing shoot has to push each year before breaking the surface; the temperature and moisture characteristics of the substrate, and hence geophyte respiration, vary with depth; the substrate horizon exploited by the adventitious roots, which average about 5cm in length, is determined by the depth of the geophyte basal-plate from which the roots emerge; and, finally, the likelihood of interference, damage or predation by most animals may be less for deeper seated geophytes (Barkham, 1980a). Planting depth also may affect vegetative reproduction and flower production has also been shown to be related to the depth of the geophyte in the substrate. The flowers of deeper geophytes have a higher probability of producing capsules containing seeds. This is probably because shallow planting tends to induce earlier flowering (Ministry of Agriculture, Fisheries & Food 1951), is more likely to lead to water shortage (Cohen, 1976), and there is less likelihood of earlier flowers being pollinated because of lower abundance of insects (Barkham, 1980b).

1.6 Research questions

Although geophytes have potential for use for extensive green roofs, there has been little research into how they perform on roofs. The aim of this study is to choose some appropriate geophyte species for green roofs as well as to investigate how substrate depth and covering plants of *Sedum* spp. affect the emergence, growth, length of foliage and flowering time and reproduction. The research questions are listed as follows.

1) Is it possible to use geophyte species for extensive green roofs?
2) How does substrate depth and the presence of a competing cover of *Sedum* species, and the interaction between these affect the emergence, growth, flowering and reproduction of each species?
3) Which species can survive, grow well and produce flower on extensive green roofs, especially in a thin substrate?
4) Are there any problems in growing geophytes on roofs?

2. Materials and Methods

2.1 Experiment 1

This experiment was set up in the winter of 2004 on the roof of a four storey of commercial building near the city centre in Sheffield UK. On the third floor of the building, an extensive green roof which contains 12 plots was installed alongside a 70 cm parapet (Fig.3.3.1). The green roof consists of root protection barriers, drainage layers and a commercial green roof substrate composed of crushed recycled brick and 10 % organic material (1:1 of Zinco semi-intensive and Zinco Sedum). The depth of substrate (5 cm and 10 cm) and covering with competing plants (with and without *Sedum*) were chosen as variables. There were three replications for each combination, in total, 22 plots were arranged randomly (Fig.3.3.2). The plot size was 60 cm x 145 cm and it was divided into 28 subplots (12 cmx24 cm). In each subplot, 3 geophytes of one species were planted in a line (Fig.3.3.3). 26 plant species were planted: *Allium cernuum, A. flavum, A. karataviense* 'Ivory queen', *A. ostrowskianum, A. unifolium, Crocus sieberi* 'Tricolor', *C. tommasinianus, C. vernus* 'Vanguard', *Iris bucharica, I. danfordiae, I. reticulata, Ixiolirion pallasii, Muscari azureum, Narcissus cyclamineus* 'February gold', *Puschkinia libanotica, Scilla siberica, Sparaxis tricolor, Tulipa bakeri* 'Lilac wonder', *T. clusiana* var. *chrysantha, T. hageri* 'Splendens', *T. humilis, T. kolpakowskiana, T. linifolia, T. saxatilis, T. tarda, T. turkestanica* and *T. urumiensis* They were obtained from Dutchbulbs (Manchester, UK). These plants were predicted to be well-adapted to extensive green roofs because they are found naturally in desert regions growing in arid stony or rocky habitats. Their characteristics are described in Table 3.3.1. They were planted on 14th January 2005. The geophytes were placed at a depth of 3 cm substrate below the surface in two different substrate total depths: one of 5cm and the other of 10 cm (Fig.3.3.4). 0.5 g of *Sedum album* seeds were sown in each plot on 30th April 2005 as covering plants. The seeds were obtained from Jelitto (Schwarmstedt, Germany). *S. album* seeds were too small to distribute over the plot, therefore they were mixed with horticultural sand. It took one year for *S. album* to cover the plots. All plots received only rain water. In the first year, leaf length (the longest stem, from proximal to apex) and germination rate (the percentage of plants which had above-ground emergence) were measured 4 times from 24th March to 28th April 2005. In the second year, the growth was measured 11 times (From March to July, 22 weeks), the measured parameters therefore were:

Leaf length
Total leaf number (including small leaves more than 5mm),
Flower height (the longest flower stem, from proximal to apex)

Proximal shoot number (the number of vegetative reproduction)

The period of above ground growth (from emergence to completely dry out)

Flowering times (from open the buds to finish flowering).

It was considered that recording the second year of growth would be important since the geophytes had overwintered on the roofs. Flowering in the spring following planting of many spring bulbs is largely determined by the state of the bulb pre-planting (i.e how it was grown prior to planting). However, growth in the second season is likely to be determined much more by the actual growing conditions *in situ*. In addition, the covering plants may have had little effect in the first year because they were installed in the middle of the experiment and they developed mainly after the geophyte growth had finished. Therefore, germination rate was the only variable measured in the first year. To test for significant difference between the treatments and the interaction, two-way ANOVA (Minitab Release 14) was used. When there were significant differences, means were separated by a Tukey test. Throughout the analysis, threshold for significance was set at $P<0.05$.

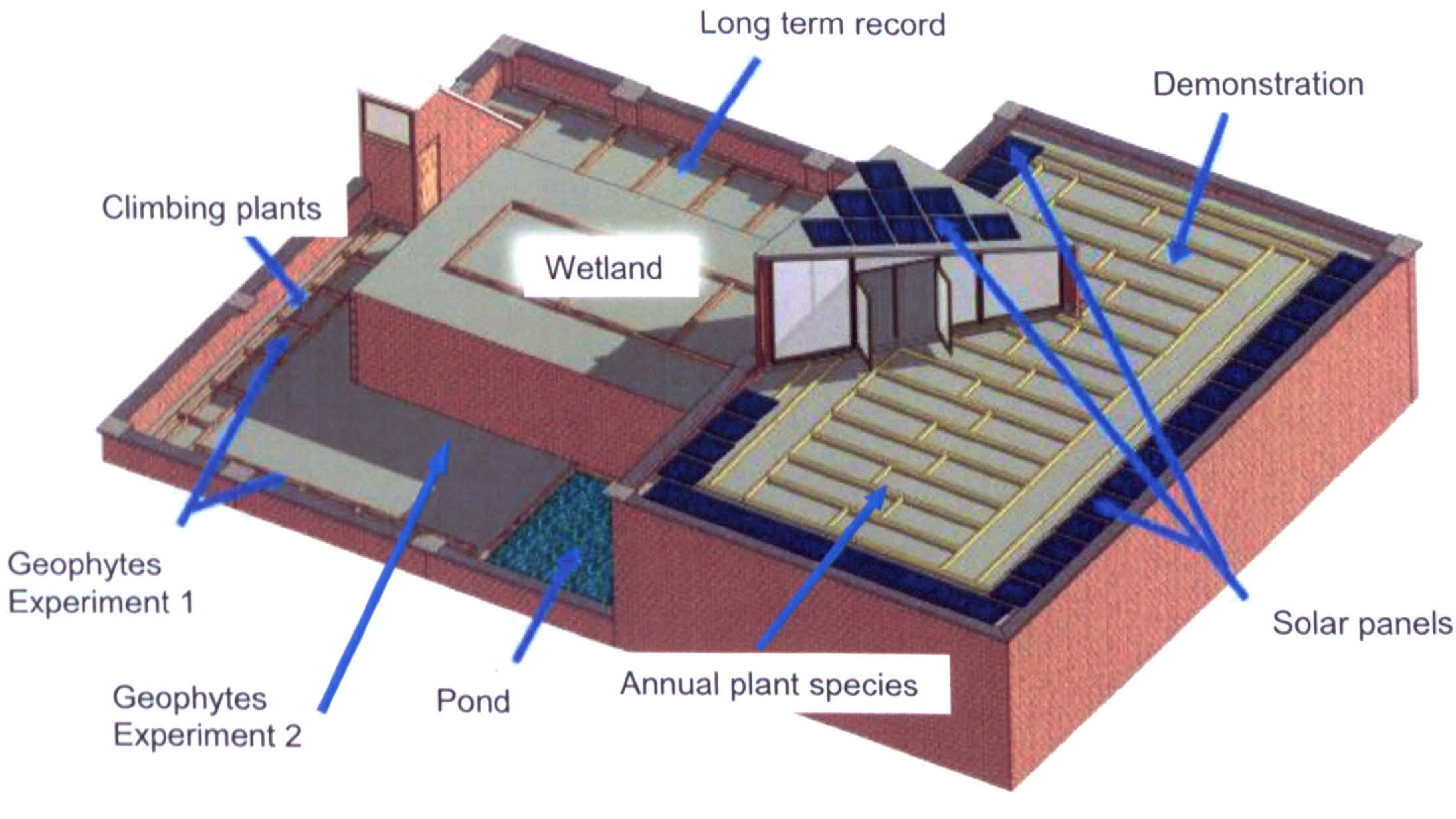


Fig.3.3.1 Overview of experimental site of the building (Source: Ark DM)

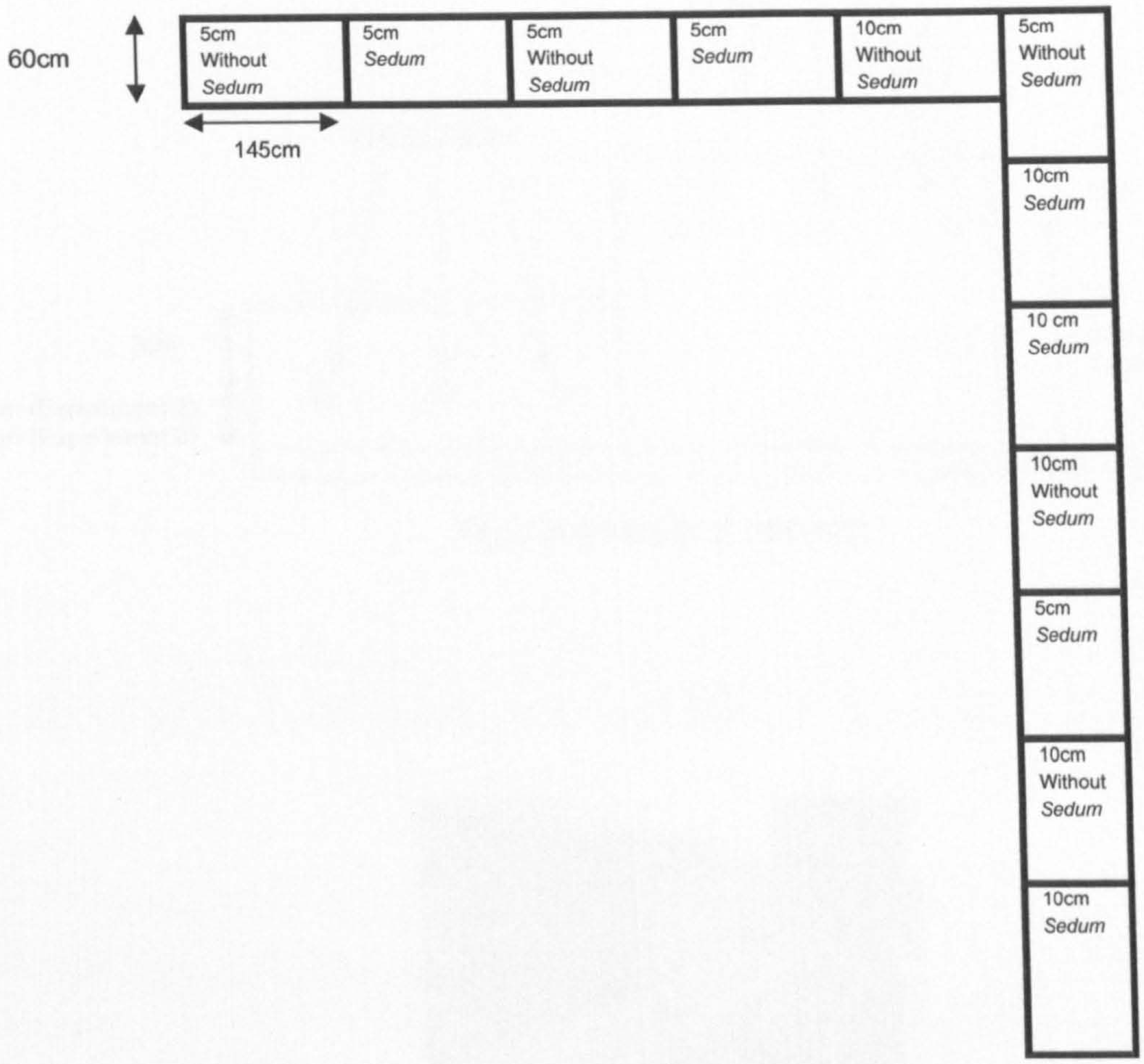


Fig.3.3.2 Overview of experimental plot on the extensive green roofs in Experiment 1

Geophytes

145cm (width) × 60cm (height)

○ ○ ○ *T. linifolia*		*C. sieberi* 'Tricolor'	*A. flavum*	*I. pallasii*	*S. tricolor*
T. hageri 'Splendens'	*A. karataviense* ivory	*M. azureum*	*C. vernus* 'Vanguard'	*C. tommasinianus*	*T. humilis*
I. bucharica		*T. kolpakowskiana*	*T. bakeri* 'Lilac wonder'	*P. libanotica*	*T. turkestanica*
A. ostrowskianum	*T. tarda*	*S. siberica*		*I. reticulata*	*T. saxatilis*
I. danfordiae	*A. unifolium*	*N. cyclamineus* 'February gold'	*T. urumiensis*		*T. clusiana chrysantha*

Fig.3.3.3 The example of arrangement plot in Experiment 1
(This shows the location of the placing of the geophytes and there were three geophytes of each species in one grid as shown in *T. uniflora,* Plants were randomly distributed in each replicate)

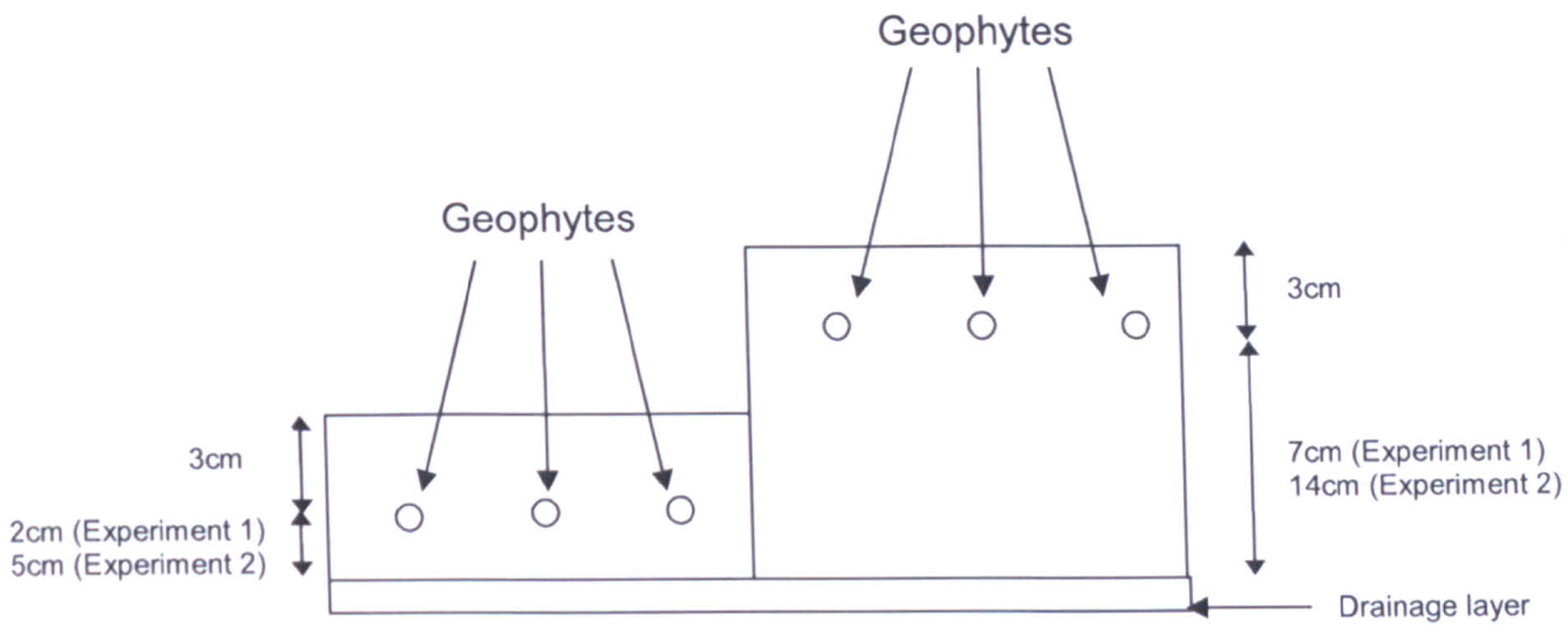


Fig.3.3.4 Depth of planting

Fig.3.3 5. Overview of Experiment 1 (2006)

2.2 Experiment 2

Experiment was set up on the same roof as Experiment 1 in the winter of 2005. Experiment 2 was carried out since the planting was delayed in Experiment 1 and it is considered that the substrate depth used in Experiment 1 (5 cm and 10 cm) might be too shallow. In addition, there are several potential geophyte species which were not able to try in Experiment 1 because of unavailability from the nursery. Trays (Size: 37 cm x 57 cm x 28 cm) were used because of their mobility, rather than constructing more wooden frames. These trays contained a drainage layer and a commercial green

roof substrate composed of crushed recycled brick and 10% organic material (1:1 of Zinco semi-intensive and Zinco Sedum). In the previous experiment by Hitchmough to investigate the performance of different substrate which were carried out on the same roof, the trays were put on the roof directly which created a problem, that the air came through the drainage layer and the substrate was consequently dried out (Htichmough, personal communications). To avoid this, 1 cm of the green roof substrate was spread below the trays. Again, the depth of substrate (8 cm and 17 cm) and covering plants (with and without *S. album*) were chosen as variables. In this experiment, the substrate was deeper than Experiment 1 because as it was mentioned above, 5 cm and 10 cm would be too thin for some geophytes. There were three replicates for each combination and they were arranged randomly. The plot (tray) was divided into 6 or 7 subplots (12.3 cm x 28.5 cm or 9.2 cm x 28.5 cm). In each subplot, 3 geophytes of one species were planted in a line (Fig.3.3.6). 18 plant species which were used were *Allium cernuum, A. ostrowskianum, A. unifolium, Iris bucharica, Ixia* 'Mixture', *Ixiolirion pallasii, Muscari azureum, Sparaxis tricolor* 'Mixed', *Tulipa batalinii* 'Bright gem', *T. hageri* 'Splendens', *T. humilis, T. kolpakowskiana, T. linifolia, T. polychroma T. tarda, T. turkestanica, T. urumiensis* and *T. wilsoniana* and they were obtained from Dutch Bulbs (Manchester, UK). Their characteristics are described in Table 3.3.1. Most of the species used were repeated from Experiment 1. However, some species such as Crocus were not used in Experiment 2 because they were unsuccessful in Experiment 1. The geophytes were planted on 21st December 2005. The geophytes were placed at a depth of 3 cm below the surface in two different substrate total depths: one of 8 cm and the other of 17 cm (Fig.3.3.4). In this experiment, cuttings of *S. album* were used since it took too long to cover the plots from seeds in Experiment 1. The growth was measured 11 times (From March to July, 22 weeks). the recorded parameters were:
Leaf length
Total leaf number (including small leaves more than 5 mm),
Flower height (the longest flower stem, from proximal to apex)
Proximal shoot number (the number of vegetative reproduction)
The period of above ground growth (from emergence to completely dry out)
Flowering time (from open the buds to finish flowering).

To test for significant difference between the treatments and the interaction, two-way ANOVA (Minitab Release 14) was used. When there were significant differences, means were separated by a Tukey test. Throughout the analysis, threshold for significance was set at $P<0.05$.

Mean monthly temperature and rainfall in Sheffield over the experimental period are shown in Figs.3.3.8 and 3.3.9. The climate of much of the UK is maritime with relatively warm winters and a likelihood of regular rainfall throughout the summer. Also, summer rainfall in much of the UK tends to be a result of frontal systems delivering long periods of relatively light rain (Dunnett, 2004c). The winter of 2005, when the geophytes were planted for Experiment 1, was mild and, overall, the amount of rainfall was above average. In the second year, the temperature was below average in the winter and exceptionally above average in the summer, and rainfall was very high in March and May.

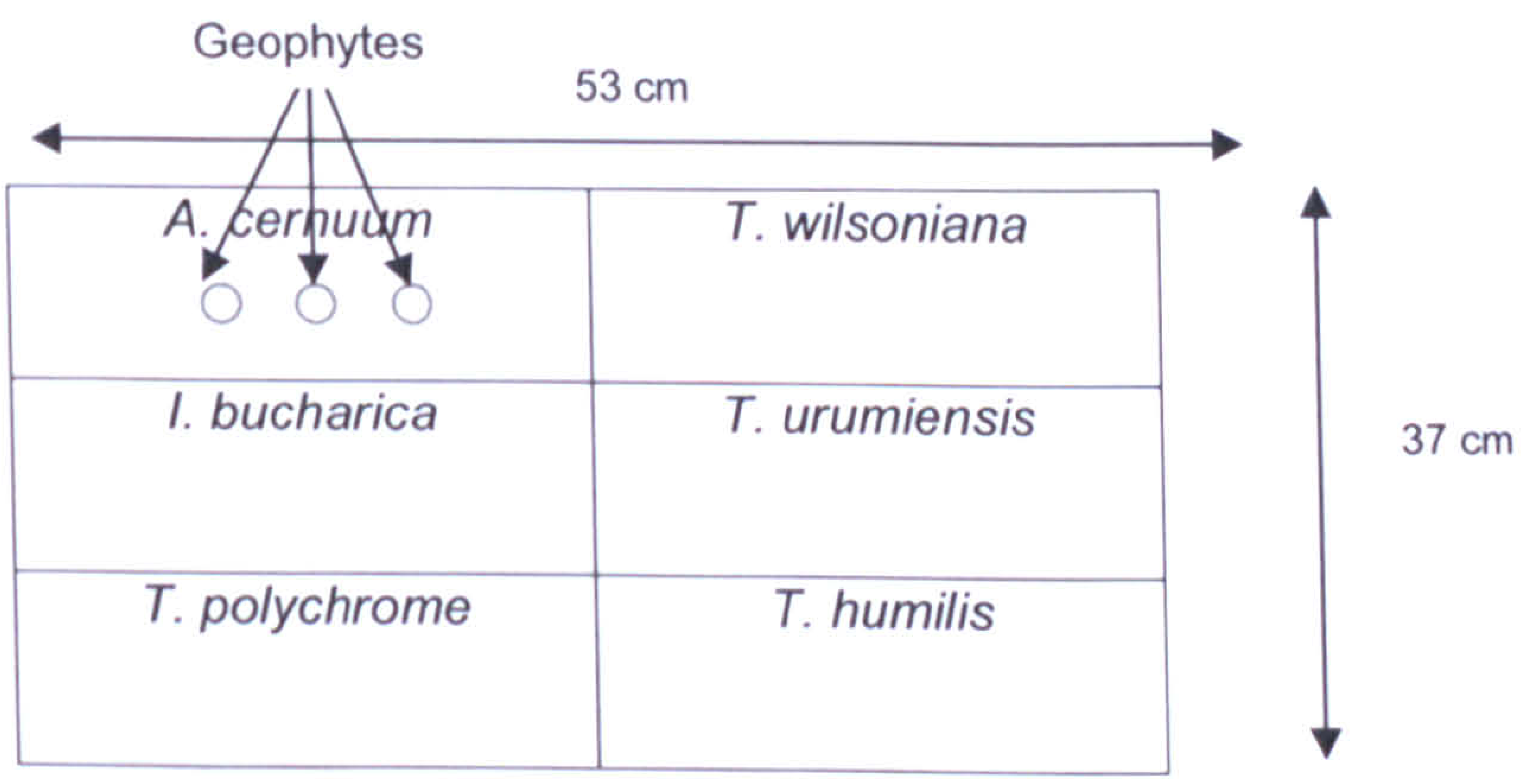


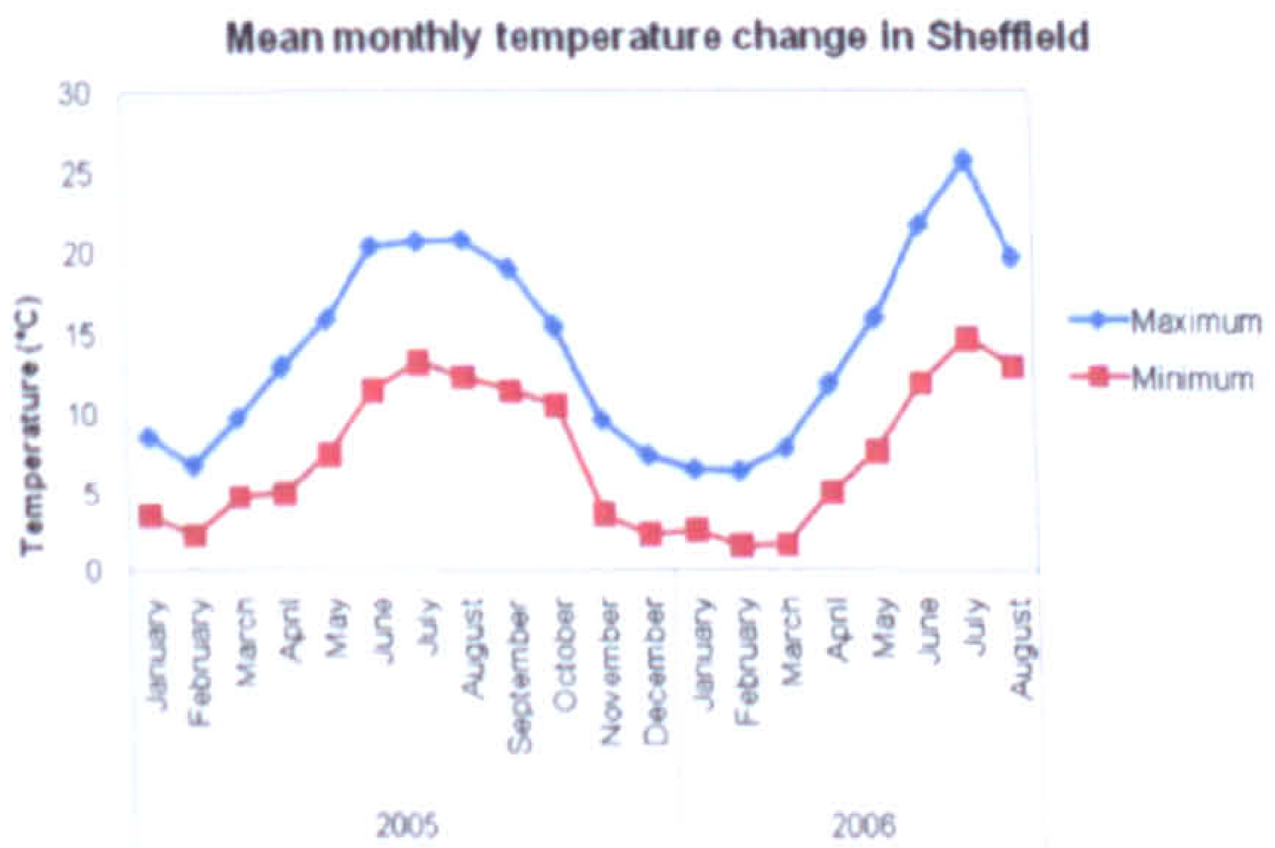
Fig.3.3.6 The example of geophyte arrangement in the tray (Experiment 2) (This shows the location of the placing of the geophytes and there were three geophytes of each species in one grid as shown in *A. cernuum*)

Fig.3.3.7. Overview of Experiment 2 (2006)

Table 3.3.1 Characteristics of geophyte species used in this study (adapted from Botschantzeva (1982), Phillips and Rix (1989),

	Family	Distribution	Typical habitat	Flower season	Height
A. cernuum	Liliaceae	North America from New York state to British Columbia southwards to Georgia and Arizona	Gravelly and rocky places in the mountains	July-August	25-45 cm
A. flavum	Liliaceae	Southern Europe from France to Greece	Dry hills	July	25cm-30cm
A. karataviense 'Ivory queen'	Liliaceae	Central Asia, especially Turkestan	Semi-desert mountain	May	15cm
A. ostrowskianum	Liliaceae	Central Asia, especially in Tien Shan, the Pamir Alai and the Ala Tau, and the eastern Turkey and the Caucasus	Stony slopes at 3000-3800m	May-June	15cm
A. unifolium	Liliaceae	N California and S Oregon in the coast ranges	Coast ranges, growing in the moist substrates in pine or mixed evergreen forest below 1200m	May-July	45cm
C. sieberi 'Tricolor'	Iridaceae	Crete and Greece	Short mountain turf or open woodland	Feb-March	8cm
C. tommasinianus	Iridaceae	Dalmatia, S Hungary, Yugoslavia and N Bulgaria	In woods and shady hillsides, especially on limestone, at ground 1000m	Feb-March	8cm
C. vernus 'Vanguard'	Iridaceae	Europe from the Pyrenees eastwards to Poland and Russia, and south to Sicily and Yugoslavia	Mountains	Feb-June	10cm
I. bucharica	Iridaceae	Central Asia, especially the Pamir Alai and Tajikistan and NE Afghanistan	Stony and grassy hills from 800 to 2400m	March-April	30cm
I. danfordiae	Iridaceae	Central Turkey, in the Taurus, in West Malatya, in Amasya and in Gümüsane	2000-3000m, on bare, earthly hills	Feb-March	10cm
I. reticulata	Iridaceae	USSR, Turkey, Iran, S Transcaucasia and Iraq	Scree and bare stony places and among scrub from 600m to 2700m	March-May	20cm
I. 'Mixture'	Iridaceae	South Africa	SW Western cape	June-July	40cm-50cm
I. pallasii	Amaryllidaceae	Western Asia from Turkey and Egypt eastwards to western Siberia	In fields and on hillsides from 200 to 2700m	June	30cm
M. azureum	Iridaceae	Caucasus and NW Turkey	High elevation	March	15cm
N. cyclamineus 'February gold'	Amaryllidaceae	NW Portugal and NW Spain	River banks and damp mountain pastures	Early March	30cm
P. libanotica	Liliaceae	Caucasus, S Turkey, N Iraq, Iran to Lebanon	In scrub, in stony places and in meadows in mountains, at up to 3000m.	March-April	15cm
S. siberica	Liliaceae	S. Russia, Caucasus and Turkey southwards to Siberia, naturalized in E Europe	Woods, scrub and among rocks, up to 2000m	March-April	10cm
S. tricolor	Iridaceae	S. Africa	Cape province	June	25cm
S. tricolor 'Mixed'	Iridaceae	S. Africa	Cape province		
T. bakeri 'Lilac wonder'	Liliaceae	Crete(Greece)	Fields and rocky places	March	25cm
T. batalinii I 'Bright gem'	Liliaceae	Iran, Uzbekistan & Turkestan (T. batalinii)	Stony hillside	April-May	30cm
T. clusiana var. *chrysantha*	Liliaceae	Iran, near Shiraz eastwards to the Himalayas from Afghanistan to Kumaon, and naturalized in S Europe	Stony mountain sides	April	20cm
T. hageri 'Splendens'	Liliaceae	Greece, Crete, Bulgaria, W Turkey	Cornfield and stony places	April	20cm
T. humilis	Liliaceae	E Turkey, N Iraq and NW Iran	Stony hillside	March	8cm-10cm
T.	Liliaceae	C Asia, especially the northern Tien	Rocky slopes up to 2000m	May	15cm

kolpakowskiana		Shan and southern Ala Tau			
T. linifolia	Liliaceae	Uzbekistan, North Iran, Afghanistan	Mountains	Mid-May	12cm
T. polychroma	Liliaceae	Iran and Afghanistan	Stony semi desert overgrown with wormwood in dry clayey and stony place	March	5-7.5cm
T. saxatilis	Liliaceae	Crete(Greece)	Fields and rocky places	Early May	15cm
T. tarda	Liliaceae	Central Asia, especially Tien Shan	Stony and rocky slopes	April	12cm
T. turkestanica	Liliaceae	Central Asia, especially Tien Shan and the Pamir Alai, and NW China	Stony slopes, by streams and on rock ledges from 1800m to 2500m	Early May	15cm
T. urumiensis	Liliaceae	Iran	Not known in the wild	April	10-15cm
T. wilsoniana	Liliaceae	N Iran in the Tabriz region, in the Elburz and in the Kopet Dağ, and in Soviet Turkmenia	Rocky and stony hills at up to 300m	April-June	



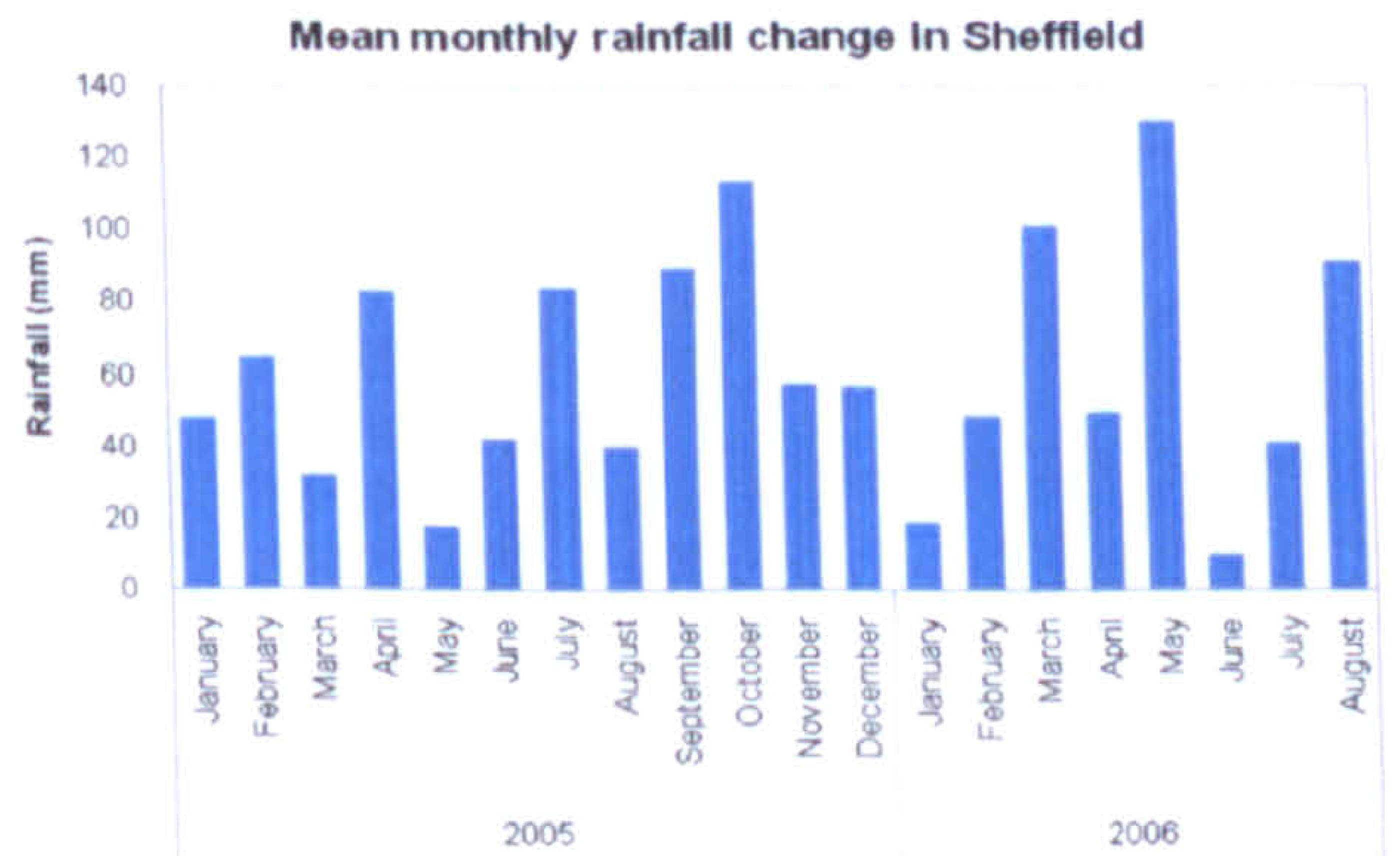


Fig.3.3.8 Mean monthly temperature change in Sheffield (Source: Meto office)
Fig.3.3.9 Mean monthly rainfall change in Sheffield (Source: Meto office)

Table 3.3.2 Pictures of geophyte species used in this study

A. cernuum	***A. flavum***	***A. karataviense* 'Ivory queen'**	***A. ostrowskianum***	***A. unifolium***
				
***C. sieberi* 'Tricolor'**	***C. tommasinianus***	***C. vernus* 'Vanguard'**	***I. bucharica***	***I. danfordiae***
				
I. reticulata	***I.* 'Mixture'**	***I. pallasii***	***M. azureum***	***N. cyclamineus* 'February gold'**

(Pictures of *C. sieberi* 'Tricolor' *C. tommasinianus I. danfordiae S. tricolor T. saxatilis* from Kelly, 2007, Picture of *I.* 'Mixture' from Dutch gardens,2008)

3. Results

3.1 Emergence

3.1.1 Total emergence

The mean total emergence of geophytes per plot in response to substrate depth and the covering plants is shown in Figs.3.3.10-3.3.12. Overall emegence in Experiment 2 was higher than Experiment 1 because deeper substrates were used and the species which showed low emergence in the first year in Experiment 1 were not used in Experiment 2.

The results indicated that total plant emergence was higher in the deeper substrate. In the first year, substrate depth had no significant impact on the emergence in both Experiment 1 and 2. However, emergence was significantly higher in the deeper substrate in the second year. This result may suggest that the substrate depth was more important for the survival rate over the winter rather than emergence after a few months of planting. Also because in the first season after planting, geophytes are able to grow on the basis of food or nutrient reserves from the previous season when they were nursery grown. Both the measure of the covering plants and of the interaction between the substrate depth and the covering plants did not show significant effect on emergence. Although the statistical analysis did not show a significant difference, the emergence was higher with *Sedum* than without. This trend was clearer in the shallow substrate. It seems that covering plants did not compete much with the geophytes but they worked as a protection layer and encouraged emergence.

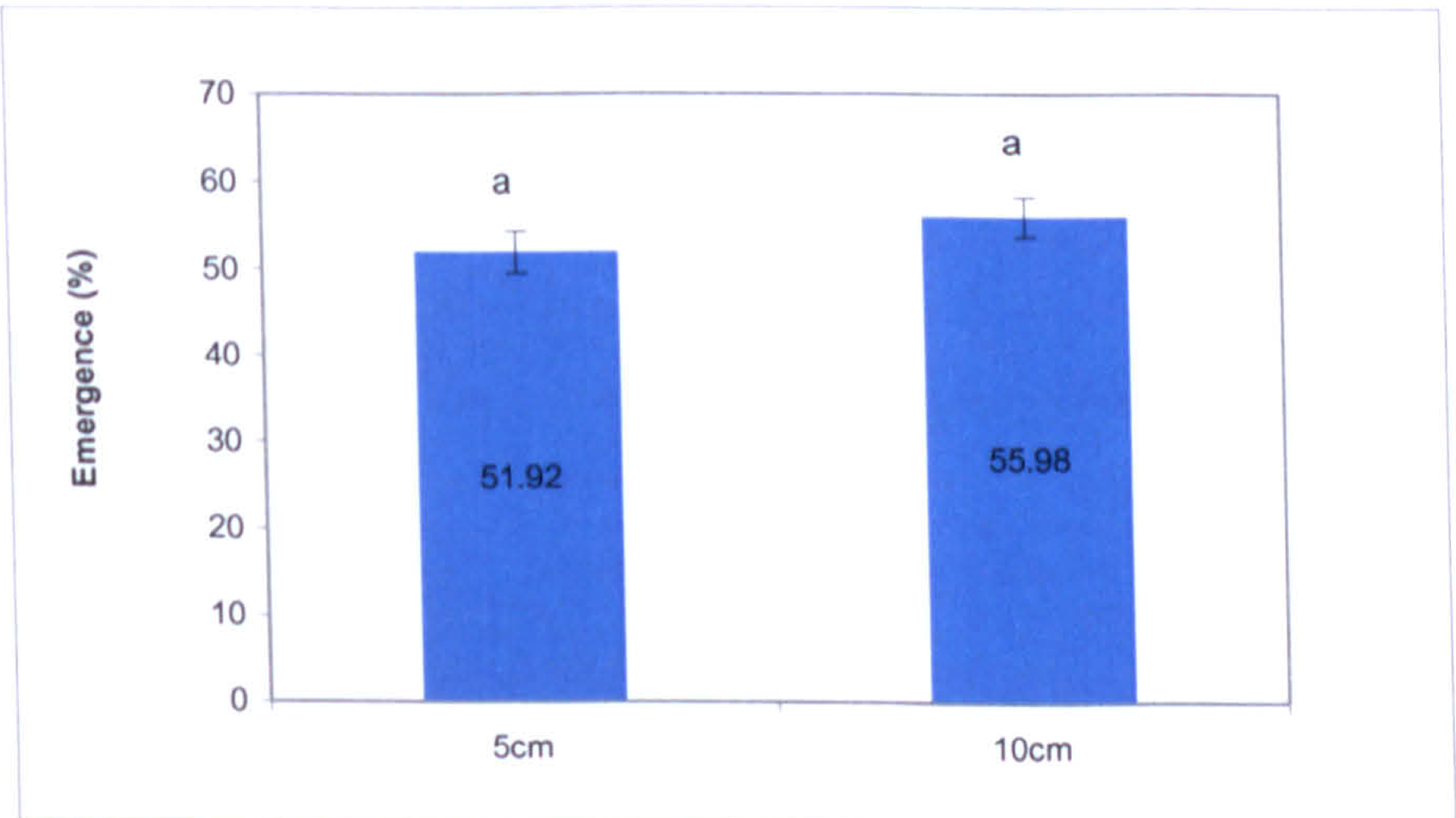


Fig.3.3.10 Mean percentage of emergence per plot in the first year (Experiment 1) Error bars represent standard error. Means with the same letter do not differ significantly from each other.

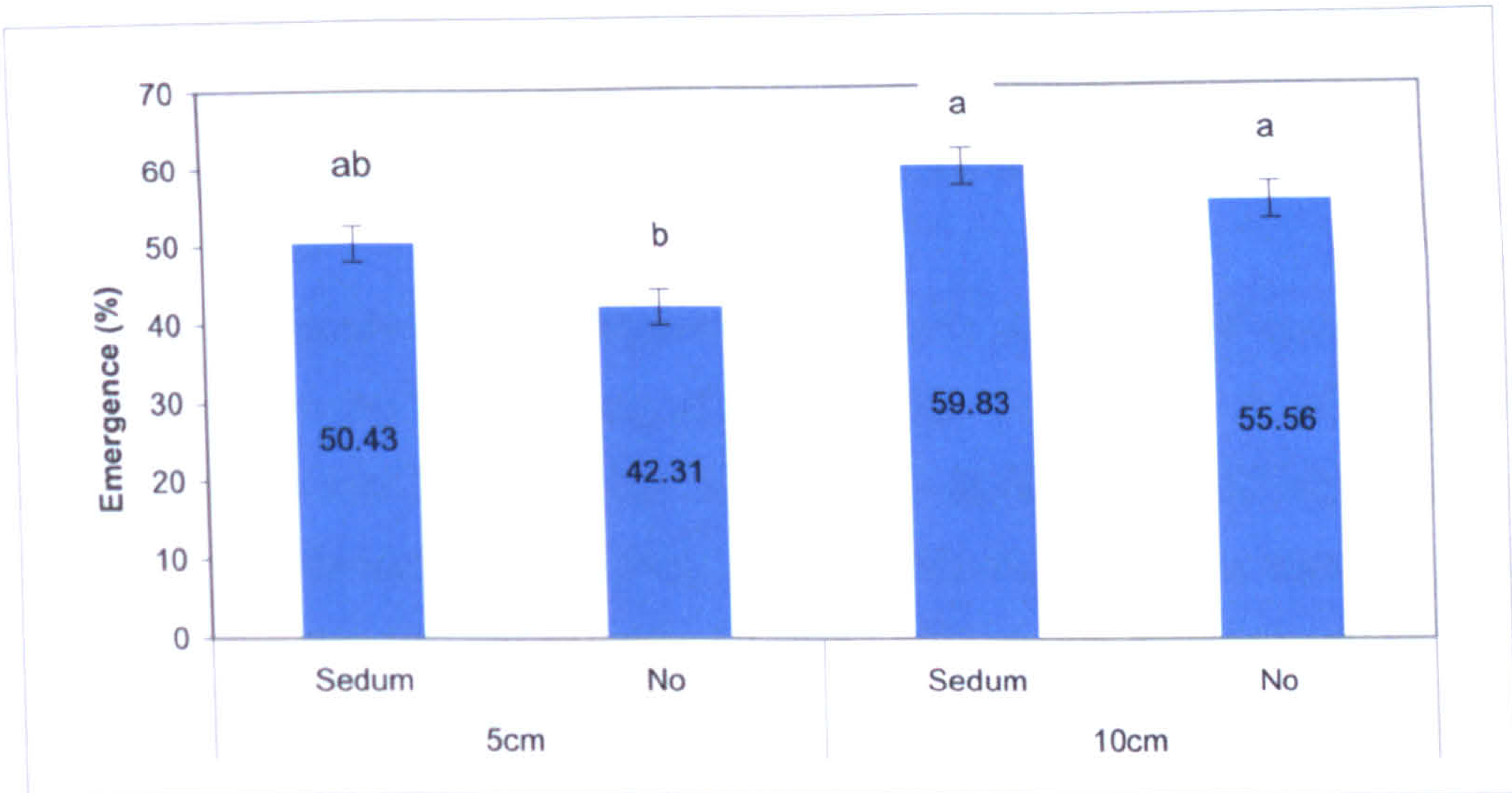


Fig.3.3.11 Mean percentage of emergence per plot in the second year (Experiment 1) Error bars represent standard error. Means with the same letter do not differ significantly from each other.

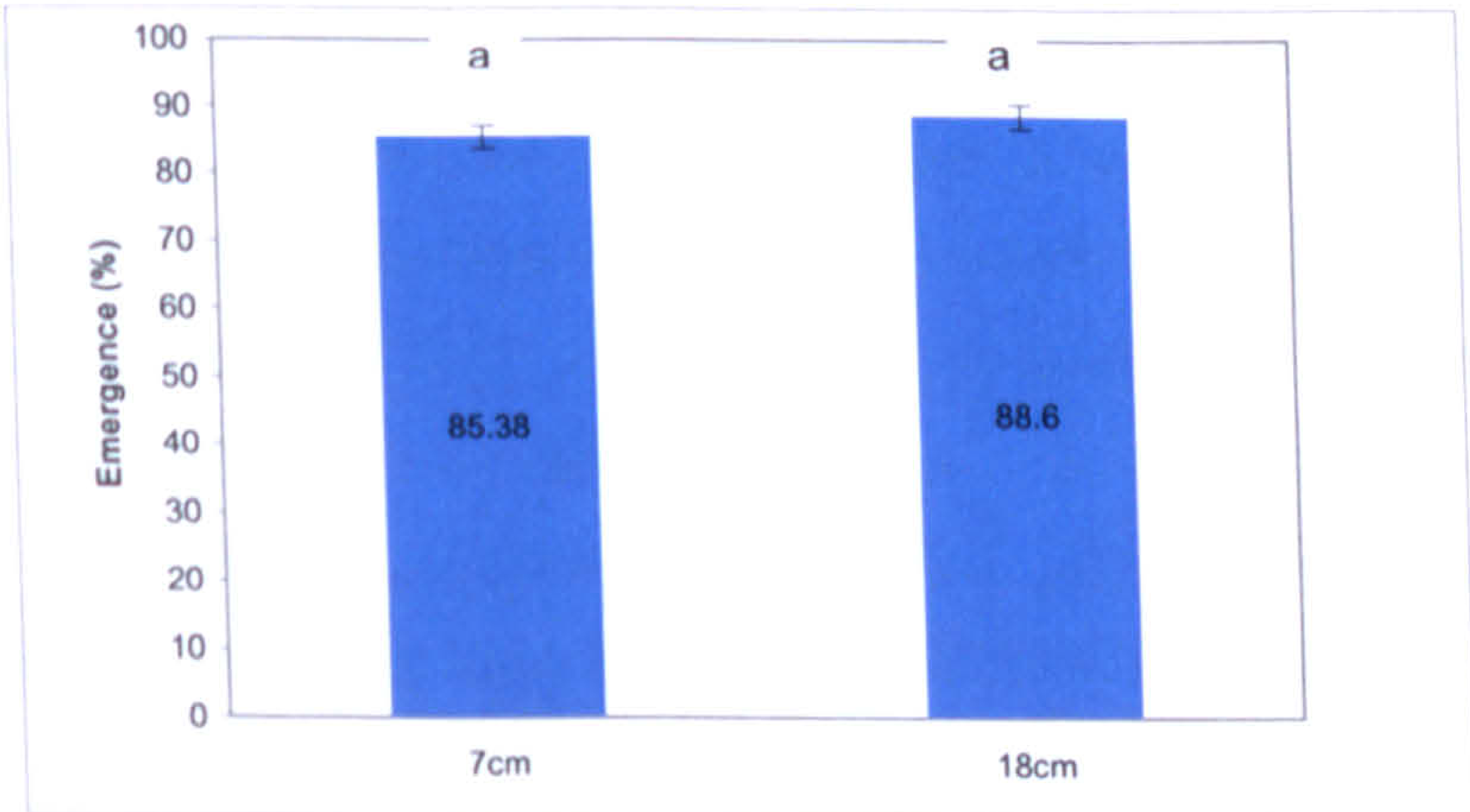


Fig.3.3.12 Mean percentage of emergence per plot in the first year (Experiment 2) Error bars represent standard error. Means with the same letter do not differ significantly from each other.

3.1.2 Emergence of individual species

Mean percentage of emergence of individual species per plot in response to the substrate depth and the covering plants is shown in Table 3.3.3. Again, the substrate depth was important for the emergence in the second year; more species had better emergence in the deep substrate. In the first year, only four species, *A. flavum, A. unifolium, I. reticulata* and *P. libanotica* were affected significantly by the substrate depth in Experiment 1 and no species were affected significantly in Experiment 2. In the second year, the substrate depth had a significant effect in the five species (*A. unifolium, N. cyclamineus* 'February gold', *S. siberica, S. tricolor, T. turkestanica).* Surprisingly, all of four species in Experiment 1 (*A. flavum, A. unifolium, P. libanotica I. reticulata)* and *A. cernuum* (Experiment 2) showed significantly higher emergence in the shallow substrate than in the deep substrate in the first year.

About half the species showed higher emergence with *Sedum*. The covering plants had a significant effect on the emergence of five species (*A. flavum, A. ostrowskianum, I. reticulata, T. linifolia* and *T. turkestanica*). Only *T. linifolia* showed higher emergence without *Sedum*. *A. flavum* was the only species which showed a significant effect of interaction between the two treatments. In this species, the percentage of emergence was much higher with *Sedum* in 5 cm than in 10 cm. These results might suggest that different species were affected differently by covering plants; some species would compete with *Sedum*, however, some species may be encouraged in their emergence by a covering of *Sedum*.

Different percentages of emergence were shown between species. However, the tendency was observed that the percentages of emergence in the first and second year showed similar figures. This indicates that the species which showed low (high) emergence in the first year had low (high) emergence in the second year as well. *I. bucharica, M. azureum, T. clusiana* var. *chrysantha* and *T. urumiensis* showed higher emergence even in 5cm in both the first and second year. On the contrary, *A. karataviense* 'Ivory queen', *C. sieberi* 'Tricolor', *C. tommasinianus, C. vernus 'Vanguard', I. danfordiae, T. bakeri* 'Lilac wonder', *T. hageri* 'Splendens', and *T. kolpakowskiana* showed low emergence in both the first and second year. In Experiment 2, most species showed high emergence, although, *A. unifolium* and *T. hageri* 'Splendens' had relatively low emergence.

Table 3.3.3 Mean percentage of emergence of individual species per plot (n=3)

Mean emergence per plot (%)														
Plant name	Experiment 1										Experiment 2			
	1st year				2nd year						1st year			
	5cm	10cm	SE	P	5cm		10cm		SE	P	7cm	18cm	SE	P
					Sedum	Without *Sedum*	*Sedum*	Without *Sedum*						
A. cernuum	-	-	-	-	-	-	-	-	-	-	77.78 a	55.56 a	11.11	ns
A. flavum	72.22a	33.33b	11.15	D<0.05	88.89a	22.22a	33.33a	33.33a	14.96	C<0.05, D*C<0 05	-	-	-	-
***A. karataviense* 'Ivory queen'**	5.56a	5.56a	5.56	ns	0a	11.11a	11.11a	33.33a	11.45	ns	-	-		-
A. ostrowskianum	94.44a	83.33a	7.50	ns	77.78a	44.44a	100a	66.67a	14.16	C<0.05	94.44 a	94.44 a	5.56	ns
A. unifolium	72 22a	27.78a	10 86	D<0 05	33.33b	44 44a	88 89a	88.89a	14 43	D<0 01	44 44	55 56	12 05	ns

						b					a	a		
C. sieberi 'Tricolor'	22.22a	16.67a	9.58	ns	22.22a	11.11a	22.22a	22.22a	13.89	ns	-	-	-	-
C. tommasinianus	0	0	-		0a	11.11a	0a	0a	5.56	ns	-	-	-	-
C. vernus 'Vanguard'	16.67a	16.67a	9.04	ns	22.22a	22.22a	33.33a	11.11a	14.43	ns	-	-	-	-
I. bucharica	94.44a	100a	3.93	ns	100	100	100	100	-	-	100	100	-	
I. danfordiae	5.56a	5.56a	5.56	ns	0a	22.22a	0a	0a	7.35	ns	-	-	-	-
I. reticulata	83.33a	44.44 b	10.65	D<0.05	44.44a	11.11a b	66.67b	11.11b	14.43	C<0.01	-	-	-	-
I. 'Mixture'	-	-	-	-	-	-	-	-	-	-	83.33 a	88.89 a	8.36	ns
I. pallasii	61.11a	72.22a	11.35	ns	66.67a	66.67a	55.56a	44.44a	17.12	ns	77.78 a	83.33 a	9.58	ns
M. azureum	94.44a	100.00 a	3.93	ns	100	100	100	100	-		100	100	-	-
N. cyclamineus 'February gold'	100	100	-	-	88.89a	66.67a	100a	100a	10.02	D<0.05	-	-	-	-
P. libanotica	55 56a	22 22b	11.11	D<0.05	55 56a	44.44a	66.67a	77.78a	16 67	ns	-	-	-	-
S. siberica	16.67a	11.11a	8.36	ns	33.33a	0b	66.67a	44.44a	14.70	D<0.01	-	-		-
S. tricolor	66 67a	66 67a	11.43	ns	0b	0b	66.67a	88.89a	10.02	D<0.01	-	-	-	-
S. tricolor 'Mixed'	-	-	-	-	-	-	-	-	-	-	66.67 a	66.67 a	11.43	ns
T. bakeri 'Lilac wonder'	44.44a	38.89a	11.94	ns	44.44a	22.22a	22.22a	11.11a	14.70	ns	-	-	-	-
T. batalinii 'Bright gem'	-	-	-	-	-	-	-	-	-	-	100	100	-	-
T. clusiana var. *chrysantha*	94.44a	94.44a	5.56	ns	100	100	100	100	-		-	-	-	-
T. hageri 'Splendens'	27.78a	16.67a	9.99	ns	11.11a	11.11a	33a	0a	11.45	ns	33.33 a	55.56 a	11.75	ns
T. humilis	72.22a	66.67a	11.15	ns	88.89a	77.78a	88.89a	77.78a	13.03	ns	100a	94.44 a	3.93	ns
T. kolpakowskiana	27.78a	5.556a	8.63	ns	22.22a	11.11a	44.44a	44.44a	15.47	ns	100	100	-	-
T. linifolia	55.56a	77.78a	11.11	ns	33.33a	66.67a	55.56a	88.89a	15.71	C<0.01	94.44 a	100a	3.93	ns
T. polychroma	-	-	-	-	-	-	-	-	-	-	100	100	-	-
T. saxatilis	50.00a	38.89a	11.98	ns	44.44a	44.44a	44.44a	77.78a	16.90	ns	-	-	-	-
T. tarda	66.67a	66.67a	11.43	ns	66.67a	77.78a	55.56a	55.56a	16.67	ns	100	100	-	-
T. turkestanica	94.44 a	100.00 a	3.928	ns	77.78 ab	11.11b	100a	77.78a b	11.79	D<0.01. C<0.01	100a	94.44 a	3.93	ns
T. urumiensis	100	100	-		88.89a	100a	100a	88.89a	7.86	ns	100a	94.44 a	3.93	ns
T. wilsoniana	-	-	-	-	-	-	-	-	-	-	94.44 a	100a	3.93	ns

Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other. D=Depth of substrate, C=Covering plants, D*C=interaction between depth of substrate and covering plants

3.2 Growth

The growth of individual plants (as measured by leaf length, leaf number, flower height) in response to the substrate depth and the covering plants is shown in Table 3.3.4. Growth was measured 11 times (From March to July, 22 weeks) and each species had a growth peak at different times. Therefore, only the maximum leaf and flower growth were shown individually. Overall growth in the deeper substrate was better; longer leaf length, larger number of leaves and higher flower height. About half the species in Experiment 1 and 8 species in Experiment 2 were affected by the substrate depth significantly and all of these species showed better growth in the deeper substrate. The exception was the leaf length of *A. unifolium*, they showed longer leaf length at 5cm, although they showed larger number of leaves. In most species in Experiment 2, the difference of growth between 7cm and 18 cm was small.

It seems that the effect of covering plants varies by species. As found in the results for emergence, about half the species showed better performance with *Sedum*. However, more species showed better growth without *Sedum* at 10 cm. The growth of three species (*S. tricolor*, *T. kolpakowskiana* and *T. turkestanica*) was affected significantly by covering plants. Only the leaf growth of *S. tricolor* showed better growth without *Sedum*. The leaf number of *T. kolpakowskiana* and both leaf and flower growth of *T. turkestanica* were increased with *Sedum*.

I. bucharica, *T. clusiana* var. *chrysantha* and *M. azureum* appeared to have acceptable growth even in 5cm of substrate, indicating that these species would be very useful for extensive green roofs. Some species such as *A. karataviense* 'Ivory queen', *C. siberi* 'Tricolor', *C. tommasinianus, C. vernus* 'Vanguard', *I. danfordiae, T. hageri* 'Splendens' did not appear to develop the sufficient growth to suggest they might be not useful on green roofs.

Table 3.3.4 Maximum growth of individual species (n=9)

			Experiment 1						Experiment 2				
			2nd year						1st year				
			5cm		10cm								
Plant name	Maximum growth	Maximum growth Date	*Sedum*	Without *Sedum*	*Sedum*	Without *Sedum*	SE	Probability	Maximum growth Date	7cm	18cm	SE	P
A. cernuum	Leaf length (cm)	-	-	-	-	-		-	27th July	8.43a	7.94a	2.19	ns
	Leaf number	-	-	-	-	-		-	27th July	1.78a	1.33a	0.43	ns
	Flower height (cm)	-			-	-		-	-	0	0	-	-
A. flavum	Leaf length (cm)	22nd May	4.34a	7.28a	16.88a	6.04a	3.67	ns	-	-	-	-	-
	Leaf number		0.89a	4 22a	4.89a	2.89a	1.57	ns	-	-	-	-	-
	Flower height (cm)	10th July	8.13a	4.21a	3.59a	8.04a	3.75	ns	-	-	-	-	-
***A. karataviense* 'Ivory queen'**	Leaf length (cm)	6th June	0a	1.89a	0a	0.22a	0.62	ns	-	-	-	-	-
	Leaf number		0a	0.3a	0a	0.22a	0.14	ns	-	-	-	-	-
	Flower height (cm)	22nd May	0a	0a	0a	3.34a	1.12	ns	-	-	-	-	-
A. ostrowskianum	Leaf length (cm)	27th April	4.46a	5.59a	2.28a	3.50a	1.62	ns	5th May	13.63 a	10.77a	1.43	ns
	Leaf number		3 56a	2 67a	0 89a	1.67a	1.02	ns	5th May	1.78a	1.56a	0.18	ns
	Flower height (cm)	-	0	0	0	0	-	-	6th June	7.79a	4.87a	1.18	ns
A. unifolium	Leaf length (cm)	27th April	10.44 a	11.22 a	3.98 a	4.21 a	1.99	D<0.01	5th May	6.53a	7.83a	2.23	ns
	Leaf number		2.78 a	3.28 a	10.44 a	9 67 a	2.24	D<0.01	5th May	2.28a	3.72a	0.81	ns
	Flower height (cm)	6th June	0a	4.90a	6.23a	1.49a	2.74	ns	6th June	4.68a	9.17a	3.75	ns
***C. sieberi* 'Tricolor'**	Leaf length (cm)	29th March	1.00a	0.37a	0.30a	0.74a	0.61	ns	-	-	-	-	-
	Leaf number		1.56a	0a	2.56a	3.56a	2.32	ns	-	-	-	-	-
	Flower height (cm)	-	0	0	0	0	-	-	-	-	-	-	-
C. tommasinianus	Leaf length (cm)	17th March	0a	0.24a	0a	0a	0.12	ns	-	-	-	-	-
	Leaf number	17th March	0a	0.11a	0a	0a	0 06	ns	-	-	-	-	-
	Flower height (cm)	-	0	0	0	0		-	-	-	-	-	-
C. vernus	Leaf length	27th April	0a	0a	2.57a	2.11a	1.36	ns	-	-	-	-	-

'Vanguard'	(cm)											
	Leaf number		0 89a	0.11a	1.00a	0.89a	0.81	ns	-	-	-	-	-
	Flower height (cm)	17th March	0a	0a	0a	1.44a	0.72	ns	-	-	-	-	-
I. bucharica	Leaf length (cm)	6th June	18.70	18.36	24.64	25.50	1.61	D<0.01	6th June	20.25 b	26.55a	0.94	D<0.01
	Leaf number		28.22a	22.44a	32.22a	30.11a	3.33	ns	6th June	20.11 a	22.61a	1.60	ns
	Flower height (cm)	17th April	17.81b	19.05b	25.29ab	26.64a	1.96	D<0.01	5th May	17.38 a	20.87a	1.30	ns
I. danfordiae	Leaf length (cm)	29th March	0a	0.7a	0a	0a	0.35	ns	-	-	-	-	-
	Leaf number		0a	0.4a	0a	0a	0.22	ns	-	-	-	-	-
	Flower height (cm)		0	0	0	0	-	-	-	-	-	-	-
I. reticulata	Leaf length (cm)	4th May	1.82b	0b	11.22a	2.68ab	2.84	D<0.05	-	-	-	-	-
	Leaf number		0.44a	0a	2.00a	0 67a	0.57	ns	-	-	-	-	-
	Flower height (cm)	13th April	2.03a	0a	0a	0a	0.68	ns	-	-	-	-	-
I. 'Mixture'	Leaf length (cm)	-	-	-	-	-	-	-	6th June	9.51b	17.36a	1.85	D<0.01
	Leaf number	-	-	-	-	-	-	-	6th June	2.72a	2.50a	0.50	ns
	Flower height (cm)	-	-	-	-	-	-	-	-	0	0	-	-
I. pallasii	Leaf length (cm)	6th June	1.36a	13.42a	12.61 a	6.06 a	4.02	D*C<0.05	6th June	14.32 a	22.80a	3.41	ns
	Leaf number		0.33a	3.67a	2.89a	1.67a	1.03	D*C<0.05	6th June	3.67a	4.83a	0.73	ns
	Flower height (cm)	6th June	0.00a	3.33a	3.58a	5.75a		ns	6th June	2.81a	10.00a	3.13	ns
M. azureum	Leaf length (cm)	22nd May	6.78a	9.13a	10.47a	10.01a	1.08	D<0.05	6th June	12.61 a	12.32a	0.70	ns
	Leaf number		2.11b	3.33ab	3.56ab	4.78a	0.63	D<0.05	6th June	4.50a	6.17a	0.99	ns
	Flower height (cm)	27th April	3.09 b	5.37 ab	7.27 ab	9.43 a	1.41	D<0.01	5th May	9.22a	7.43a	0.86	ns
N. cyclamineus 'February gold'	Leaf length (cm)	4th May	0.33b	6.08b	21.66a	18.90a	2.223	D<0.01	-	-	-	-	-
	Leaf number		0.78b	2.11 b	8.11 a	8.56 a	1.24	D<0.01	-	-	-	-	-
	Flower height (cm)	27th April	0b	2.65b	21.51a	21.39 a	2.89	D<0.01	-	-	-	-	-
P. libanotica	Leaf length (cm)	27th April	3.86a	1.62a	3.14a	6.12a	1.39	ns	5th May	6.84a	6.00a	1.25	ns
	Leaf number		1.22a	0.78a	1.63a	2.00a	0.63	ns	5th May	1.44a	1.44a	0.29	ns
	Flower height (cm)	13th April	2.27a	1.13a	0.78a	4.52a	1.27	ns	23rd April	5.06a	3.10a	1.27	ns
S. siberica	Leaf length (cm)	22nd May	1.14ab	0b	6.18a	4.63ab	1.49	D<0.01	-	-	-	-	-
	Leaf number		1.44a	0a	3.11a	2.00a	1.08	ns	-	-	-	-	-
	Flower height (cm)	13th April	0.89a	0a	1.61a	2.33a	0.93	ns	-	-	-	-	-
S. tricolor	Leaf length (cm)	22nd May	0b	0b	2.88b	8.17a	1.03	D<0.01 C<0.05 D*C<0.05	-	-	-	-	-
	Leaf number		0b	0b	1.44 b	5.44a	0.68	D<0.01 C<0.01 D*C<0.01	-	-	-	-	-
	Flower height (cm)	-	0	0	0	0	-	-	-	-	-	-	-
S. tricolor 'Mixed'	Leaf length (cm)	-	-	-	-	-	-	-	6th June	4.17b	8.52a	1.35	D<0.05
	Leaf number	-	-	-	-	-	-	-		1.33a	3.44a	0.54	D<0.01
	Flower height (cm)	-	-	-	-	-	-	-	6th June	1.19a	1.05a	1.12	ns
T. bakeri 'Lilac wonder'	Leaf length (cm)	27th April	7.77a	1.50a	1.20a	0.78a	1.99	ns	-	-	-	-	-
	Leaf number		1.89a	0.78a	0.22a	0.33a	0 60	ns	-	-	-	-	-
	Flower height (cm)	27th April	0a	1.48a	0a	0a	0.74	ns	-	-	-	-	-
T. batalinii 'Bright gem'	Leaf length (cm)	-	-	-	-	-	-	-	6th June	21.50 a	19.62a	0.95	ns
	Leaf number	-	-	-	-	-	-	-		6 06a	5.83a	0.11	ns
	Flower height (cm)	-	-	-	-	-	-	-	23rd May	22.07 a	19.57a	1.50	ns
T. clusiana var. *chrysantha*	Leaf length (cm)	27th April	12.94a	13.81a	13.99a	14.21a	1.64	ns	-	-	-	-	-
	Leaf number		7.33a	6.78a	7.67a	8.78a	0.96	ns	-	-	-	-	-
	Flower height (cm)	4th May	14.04a	13.15a	10.91a	17.19a		ns	-			-	
T. hageri 'Splendens'	Leaf length (cm)	13th April	1.68a	1.11a	3.89a	0a	1.41	ns	23rd April	2.43a	3.60a	1.21	ns
	Leaf number		0.33a	0.33a	0.78a	0a	0.33	ns		0.94a	1.39a	0.44	ns
	Flower height (cm)	4th May	0a	1.03a	0a	0a	0.52	ns	5th May	0a	1.06a	0.51	ns
T. humilis	Leaf length (cm)	13th April	6.87a	5.66a	5.88a	7.50a	1.46	ns	23rd April	13.26 a	12.98a	0.723	ns
	Leaf number		4 67a	5.78a	6 22a	6.11a	1.47	ns		3 56a	3 44a	0.18	ns
	Flower height (cm)	13th April	3.66a	3.54a	5.96a	7.40a	1.75	ns	13th April	9.54a	7.42b	0.52	D<0.01
T. kolpakowskiana	Leaf length (cm)	13th April	2.14a	0a	5.07a	3.26a	1.50	D<0.05	23rd April	9.64a	8.02a	1.24	ns
	Leaf number		1.56ab	0b	3.44 a	0.44ab	0.89	C<0.05		2.56a	2.44a	0.29	ns

	Flower height (cm)	13th April	0a	0a	3.42a 0a	0a	0.87	ns	23rd April	5.68a	2.96a	1.51	ns
T. linifolia	Leaf length (cm)	27th April	1.68b	3.28ab	5.09ab	7.57a	1.45	D<0.05	23rd May	10.37 a	9.79a	1.45	ns
	Leaf number		2.33a	2.56a	4.00a	6.56a	1.47	ns		5.00a	4.89a	0 63	ns
	Flower height (cm)	4th May	2.23a	2.77a	3.67a	5.71a	1.73	ns	23rdMay	0a	1.02a	0.72	ns
T. polychroma	Leaf length (cm)	-	-	-	-	-	-	-	23rd April	13.74 a	13.54a	0.98	ns
	Leaf number	-	-	-	-	-	-	-		3.33a	3.17a	0.24	ns
	Flower height (cm)	-	-	-	-	-	-	-	23rd April	4.24b	11.31a	1.64	D<0.0 1
T. saxatilis	Leaf length (cm)	29th March	5.40a	3.77a	3.03a	4.39a	1.88	ns	-	-	-	-	-
	Leaf number		2.22a	2.00a	0.56a	0.56a	0.81	ns	-	-	-	-	-
	Flower height (cm)		0	0	0	0	-	-	-	-	-	-	-
T. tarda	Leaf length (cm)	27th April	5.23a	7.96a	5.16a	5.37a	1.73	ns	23rd May	10.71 a	13.02a	1.09	ns
	Leaf number		4.33a	4.44a	4.00a	3.56a	1.41	ns		4.89a	4.94a	0.39	ns
	Flower height (cm)	27th April	5.34a	7.07a	4.98a	4.66a	1.60	ns	5th May	3.22b	11.16a	1.13	D<0.0 1
T. turkestanica	Leaf length (cm)	27th April	13.66a	1.67b	18.67a	16.23a	2.67	D<0.01 C<0.05	23rd April	16.34 a	13.83a	1.73	ns
	Leaf number		5.00ab	1.11b	5.44a	3.00ab	1.11	C<0.01		1.67a	1.72a	0.19	ns
	Flower height (cm)	13th April	13.03ab	1.89b	18.39a	14.77a	3.00	D<0.01 C<0 05	13th April	13.24 a	8.52a	1.80	ns
T. urumiensis	Leaf length (cm)	22nd May	5.87ab	3.32b	10.48a	10.19a	1.38	D<0.01	23rd May	17.21 a	10.99b	1.71	D<0.0 5
	Leaf number		5.11a	1.89a	6.22a	6.11a	1.34	ns		5.22a	2.89b	0.49	D<0.0 1
	Flower height (cm)	4th May	2.71a	2.87a	5.85a	3.54a	1.50	ns	5th May	11.20 a	7.58a	1.57	ns
T. wilsoniana	Leaf length (cm)	-	-	-	-	-	-	-	23rd May	17.24 a	18.01a	0.938	ns
	Leaf number	-	-	-	-	-	-	-		1.44a	1.22a	0.28	ns
	Flower height (cm)	-	-	-	-	-	-	-	23rd May	0a	0.99a	0.70	ns

Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other. SE= Standard Error, D=Depth of substrate, C=Covering plants, D*C=interaction between depth of substrate and covering plants

3.3 Foliage and Flower performance of individual species

The mean length of the periods of above ground growth and flowering times of each species of plant in response to the substrate depth and the covering plants are shown in Table 3.3.5. As with the results for emergence and growth, many species showed better above ground growth and flower performance in the deeper substrate. In Experiment 1, 6 species (*A. unifolium, N. cyclamineus* 'February gold', *S. siberica, S. tricolor, T. clusiana* var. *chrysantha* and *T turkestanica*) were affected by the substrate depth significantly in the length of the period of above ground growth, whereas with the flowering times, 3 species (*M. azureum, N. cyclamineus* 'February gold', *S. siberica*) were affected. In Experiment 2, only one species (*S. tricolor*) were affected by the substrate depth significantly in the length of the period of above ground growth and with the flowering times, 6 species were affected.

Again, it seems that the effect of covering plants was different for different species. However, most of the geophyte species tested were not affected by *Sedum* spp. Only 3 species were affected by the covering plants. *S. tricolor* had a longer the period of above ground growth without *Sedum*, whereas *T. kolpakowskiana* and *T. turkestanica* had better performance with *Sedum*.

The flowering season of each species is shown in Table 3.3.6. The combination of geophyte species resulted in over four months of flowering time. The greatest number of species was flowering from at the end of April to the beginning of May. Generally, the flowering season of the geophytes was not long and lasted less than two months. *M. azureum, I. reticulata*, and *P. libanotica* showed long flowering seasons since individuals succeeded each other in flower, however, the latter two showed low percentage of flowering. Interestingly, the late flowering species (e.g. *Allium* spp., *I. pallasii, S. tricolor* 'Mixed' and *T. hageri* 'Splendens') were not very successful and tended to be short flowering. *A. cernuum, A. ostrowskianum, C. sieberi* 'Tricolor', *C. tommasinianus, I. danfordiae, I.* 'Mixture', *S. tricolor* and *T. saxatilis* did not flower at all, and these plants are not recommended to use for extensive green roofs. However, they may be able to perform better in the greater substrate depth. It is worth to note that *A. cernuum* is commonly used for green roofs in North America. According to Monterusso, et al. (2005), *A. cernuum* was suitable for unirrigated 10 cm depth of extensive green roofs in Michigan, US. In addition, *C. tommasinianus* has been fairly successful at green roofs at the depth of 20cm in Moorgate Crofts in Rotherham (Dunnett, personal communications).

Changes in flower height of successful species (*I. bucharica, M. azureum, N. cyclamineus* 'February gold', *T. clusiana* var. *chrysantha, T. humilis, T. polychroma, T. tarda, T. turkestanica, T. urumiensis*) over time are shown in Fig.3.3.13. The figure was the average of the result of Experiment 1 at 10cm of both with and without *Sedum* in the second year. The result of *T. polychroma* was in Experiment 2 at 7cm substrate (only this species in Experiment 2). Combining species with the different heights: taller species (*I. bucharica, N. cyclamineus* 'February gold'), medium height species (*T. clusiana* var. *chrysantha, T. turkestanica*), shorter species (*M. azureum, T. humilis, T. polychroma, T. tarda, T. urumiensis*) makes it possible to have visually interesting green roofs. Among these species, the largest number of species showed the highest flower height on 27th April.

Table 3.3.5 Mean the period of above ground growth and flowering times of each species (week, n=9)

Plant name		Experiment 1						Experiment 2			
		2nd year						1st year			
		5cm		10m							
		Sedum	Without *Sedum*	*Sedum*	Without *Sedum*	SE	Probability	7cm	18cm	SE	Probability
A. cernuum	Foliage	-	-	-	-		-	11.11a	7.89a	1.86	ns
	Flowering	-	-	-	-		-	0	0	-	-
A. flavum	Foliage	13.56a	4.00b	3.56b	5.33ab	2.46	D*C<0.05	-	-	-	-
	Flowering	1.56a	0.67a	0.22a	0.89a	0.45	ns	-	-	-	-

***A. karataviense* 'Ivory queen'**	Foliage	0.00a	1.11a	0.44a	3.11a	1.12	ns	-	-	-	-
	Flowering	0a	0a	0a	0.67a	0.24	ns	-	-	-	-
A. ostrowskianum	Foliage	4.00a	5.33a	7.56a	7.56a	1.74	ns	11.56a	9.33a	0.93	ns
	Flowering	0	0	0	0	-	-	2.00a	1.00b	0.24	D<0.01
A. unifolium	Foliage	4.44b	4.44b	10.89ab	13.33a	1.98	D<0.01	5.11a	6.44a	1.49	ns
	Flowering	0a	0.44a	0.44a	0.22a	0.24	ns	0.33a	0.67a	0.24	ns
***C. sieberi* 'Tricolor'**	Foliage	1.78a	0.44a	0.67a	2.00a	0.96	ns	-	-	-	-
	Flowering	0	0	0	0	-	-	-	-	-	-
C. tommasinianus	Foliage	0a	0.22a	0a	0a	0.11	ns	-	-	-	-
	Flowering	0	0	0	0	-	-	-	-	-	-
***C. vernus* 'Vanguard'**	Foliage	1.55a	0.67a	2.44a	1.56a	1.17	ns	-	-	-	-
	Flowering	0a	0a	0a	0.22a	0.11	ns	-	-	-	-
I. bucharica	Foliage	16.00a	14.67a	16.00a	16.00a	0.67	ns	12.33a	12.11a	0.25	ns
	Flowering	2.00a	1.78a	2.22a	2.22a	0.25	ns	2.67b	3.44a	0.25	D<0.05
I. danfordiae	Foliage	0a	0.89a	0a	0a	0.24	ns	-	-	-	-
	Flowering	0	0	0	0	-	-	-	-	-	-
I. reticulata	Foliage	2.22a	0.67a	5.56a	1.56a	1.38	ns	-	-	-	-
	Flowering	0.44a	0a	0.22a	0.44a	0.29	ns	-	-	-	-
***I.* 'Mixture'**	Foliage	-	-	-	-	-	-	9.78a	11.11a	1.23	ns
	Flowering	-	-	-	-	-	-	0	0	-	-
I. pallasii	Foliage	2.00a	7.78a	5.78a	4.00a	1.91	ns	10.56a	10.78a	1.37	ns
	Flowering	0.22a	0.22a	0 22a	0.44a	0.24	ns	0.22a	0.56a	0.19	ns
M. azureum	Foliage	13.56a	15.78a	15.78a	14.89a	0.62	D*C<0.05	13.67a	14.11a	0.37	ns
	Flowering	2.67b	4.22ab	6.22a	5.56 a	0.68	D<0.01	4.56a	3.78a	0.30	ns
***N. cyclamineus* 'February gold'**	Foliage	5.33a	6.67a	12.89b	13.56b	1.18	D<0.01	-	-	-	-
	Flowering	0b	0 67b	3.11a	4.00a	0.44	D<0.01	-	-	-	-
P. libanotica	Foliage	4.89a	2.89a	4.89 a	7.33 a	1.55	ns	6.00a	5.44a	1.06	ns
	Flowering	0.67a	0.44a	0.67a	1.78a	0.48	ns	1.78a	1.44a	0.42	ns
S. siberica	Foliage	3.11ab	0b	7.78a	4.89ab	1.79	D<0.05	-	-	-	-
	Flowering	0a	0a	0.89a	1.33a	0.44	D<0.05	-	-	-	-
S. tricolor	Foliage	0c	0c	6.22b	13.11a	1.39	D<0.01 C<0.05 D*C<0.05	-	-	-	-
	Flowering	0	0	0	0	-	-	-	-	-	-
***S. tricolor* 'Mixed'**	Foliage	-	-	-	-	-	-	6.22b	11.44a	1.25	D<0.01
	Flowering	-	-	-	-	-	-	0.11a	0.11a	0.11	ns
***T. bakeri* 'Lilac wonder'**	Foliage	0.89a	1.11a	1.78a	0.67a	0.97	ns	-	-	-	-
	Flowering	0a	0.22a	0.22a	0a	0.16	ns	-	-	-	-
***T. batalinii* 'Bright gem'**	Foliage	-	-	-	-	-	-	18.22a	11.44a	4.74	ns
	Flowering	-	-	-	-	-	-	2.00a	1.89a	0.08	ns
T. clusiana* var. *chrysantha	Foliage	11.33a	12.67a	14.44a	14.67a	0.98	D<0.05	-	-	-	-
	Flowering	1.78a	1.78a	1.78a	1.78a	0.32	ns	-	-	-	-
***T. hageri* 'Splendens'**	Foliage	1.33a	2.00a	3.11a	0a	1.36	ns	2.56a	5.11a	1.21	ns
	Flowering	0	0.22	0	0	0.11	ns	0b	0.56a	0.15	D<0.05
T. humilis	Foliage	7.33a	6.89a	6.44a	7.56a	1.40	ns	10.67a	11.33a	0.50	ns
	Flowering	1.78a	1.11a	1.11a	1.56a	0.54	ns	4.00a	3.33b	0.23	D<0.05
T. kolpakowskiana	Foliage	2.67a	0.67a	5.78a	3.56a	1.66	ns	11.33a	9.89a	0.83	ns
	Flowering	0.44a	0a	0.67a	0a	0.22	C<0.05	1.00a	0.56a	0.28	ns
T. linifolia	Foliage	3.56a	5.78a	6.22a	10.44a	1.92	ns	12.33a	12.67a	0.73	ns
	Flowering	0.44a	0.67a	0.67a	1.11a	0.33	ns	0a	0.11a	0.08	ns
T. polychroma	Foliage	-	-	-	-	-	-	11.89a	13.67a	0.47	ns
	Flowering	-	-	-	-	-	-	1.67b	3.11a	0.31	D<0.01
T. saxatilis	Foliage	2.89a	2.22a	3.78a	6.44a	1.58	ns	-	-	-	-
	Flowering	0	0	0	0	-	-	-	-	-	-
T. tarda	Foliage	6.89a	8.22a	6.67a	7.11a	2.23	ns	11.56a	13.22a	0.68	ns
	Flowering	1.33a	1.56a	1.11a	1.33a	0.40	ns	1.78b	3.00a	0.20	D<0.01
T. turkestanica	Foliage	8.89a	1.11b	14.22a	10.89a	1.76	D<0.01 C<0.01	12.33a	11.78a	0.92	ns
	Flowering	2.67a	0.44b	2.89a	2.44a	0.54	C<0.05	2 00a	1.56a	0.31	ns
T. urumiensis	Foliage	10.00a	9.56a	11.11a	9.33a	1.49	ns	14.33a	12.44a	0.77	ns
	Flowering	1.56a	1.56a	2.22a	1.78a	0.51	ns	2.89a	2.00a	0.33	ns
T. wilsoniana	Foliage	-	-	-	-	-	-	13.11a	13.56a	0.64	ns
	Flowering	-	-	-	-	-	-	0a	0.11a	0.08	ns

Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other. SE= Standard Error, D=Depth of substrate, C=Covering plants, D*C=interaction between depth of substrate and covering plants

Table 3.3.6 Summary of flowering season of each species

	March	April	May	June	July
A. cernuum					
A. flavum					
A. karataviense 'Ivory queen'					
A. ostrowskianum					
A. unifolium					
C. sieberi 'Tricolor'	No				
C. tommasinianus	No				
C. vernus 'Vanguard'					
I. bucharica					
I. danfordiae	No				
I. reticulata					
I. 'Mixture'	No				
I. pallasii					
M. azureum					
N. cyclamineus 'February gold'					
P. libanotica					
S. siberica					
S. tricolor	No				
S. tricolor 'Mixed'					
T. bakeri 'Lilac wonder'					
T. batalinii 'Bright gem'					
T. clusiana var. *chrysantha*					
T. hageri 'Splendens'					
T. humilis					
T. kolpakowskiana					
T. linifolia					
T. polychroma					
T. saxatilis	No				
T. tarda					
T. turkestanica					
T. urumiensis					
T. wilsoniana					

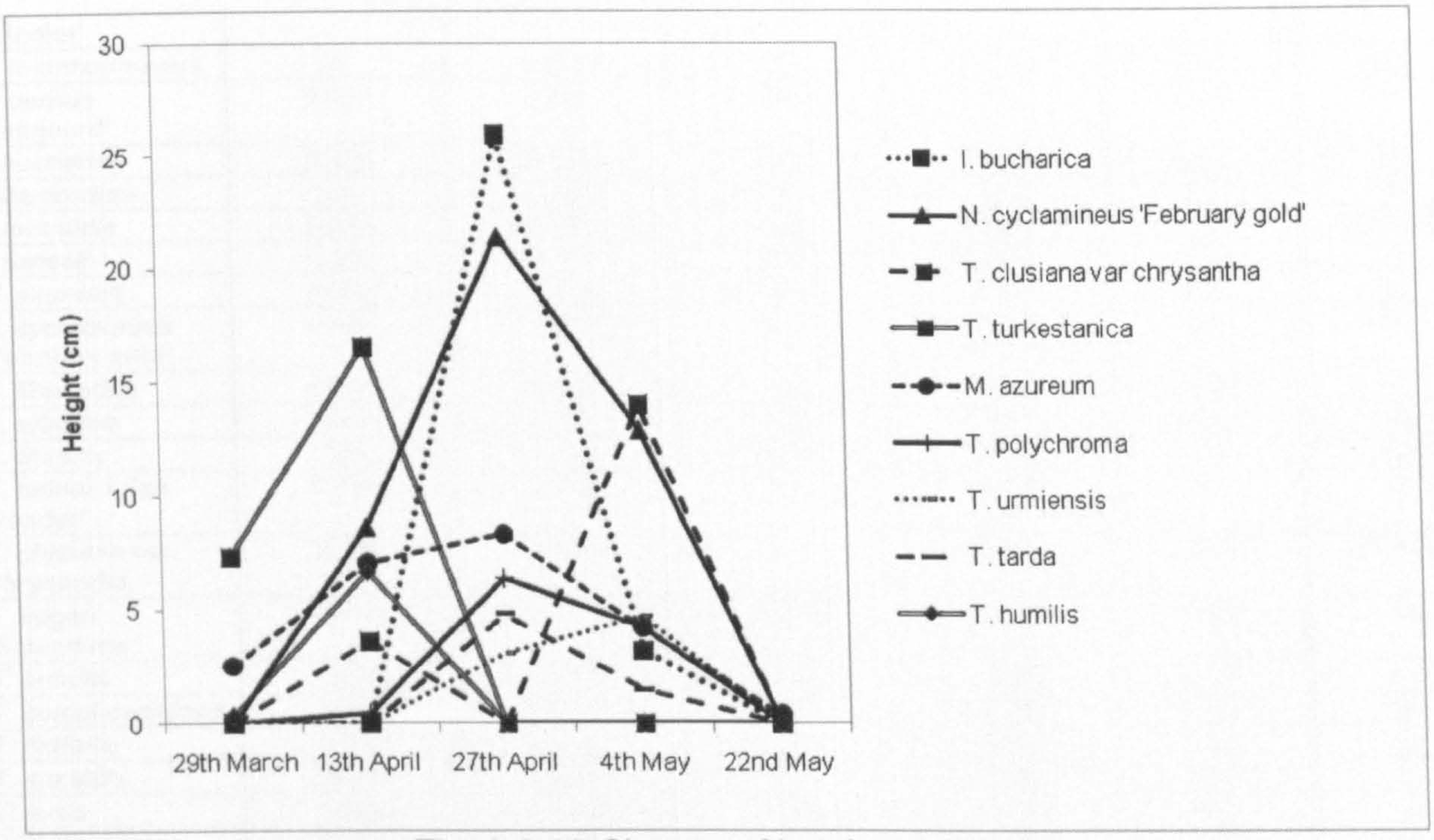


Fig. 3.3.13 Change of height over time

3.4. Vegetative reproduction of each species

Maximum proximal shoot number of each species in response to the substrate depth and the covering plants is shown in Table 3.3.7. Most emerged plants had only one proximal shoot in the first year, however, the number increased in the second year because of vegetative reproduction. Therefore, in this study, the maximum proximal shoot number was treated as the indicator of vegetative reproduction. The result showed that many species had better reproduction in the deeper substrate. In *A. unifolium, N. cyclamineus* 'February gold' and *S. tricolor,* the substrate depth made a significant difference. Two species (*I. reticulata* and *T. turkestanica*) appeared to show a significant positive effect with covering plants - they had more shoots with *Sedum*. For some species, the effects of covering plants varied according to the substrate depths. In 5cm substrate, more species had better reproduction with *Sedum* however, it was the opposite in 10cm. This phenomenon was observed significantly in *T. clusiana* var. *chrysantha*. Good reproduction was observed in *I. bucharica, N. cyclamineus* 'February gold', *T. clusiana* var. chrysantha, *T. humilis* and *T. urumiensis.*

Table 3.3.7 Mean number of proximal shoots of individual species (n=9)

	5cm		10cm			
Plant name	*Sedum*	Without *Sedum*	*Sedum*	Without *Sedum*	SE	Probability
A. flavum	2.22a	1.22a	0.67a	1.78a	0.67	ns
***A. karataviense* 'Ivory queen'**	0a	0.22a	0.11a	0.33a	0.15	ns
A. ostrowskianum	1.22a	1.67a	2.89a	3.00a	0.77	ns
A. unifolium	0.89b	0.67b	2.67a	2.56a	0.40	D<0.01
C. sieberi	0.33a	0.11a	0.33a	0.67a	0.33	ns

'Tricolor'						
C. tommasinianus	0a	0.11a	0a	0a	0.06	ns
***C. vernus* 'Vanguard'**	0.89a	0.22a	0.67a	0.22a	0.39	ns
I. bucharica	5.00a	4.33a	4.78a	4.89a	0.46	ns
I. danfordiae	0a	0.44a	0a	0a	0.15	ns
I. reticulata	0.56a	0.22a	0.89a	0.22a	0.24	C<0.05
I. pallasii	0.78a	0.67a	0.56a	0.44a	0.19	ns
M. azureum	1.00a	1.33a	1.22a	1.78a	0.23	ns
***N. cyclamineus* 'February gold'**	1.44b	1.33b	3.67a	3.67a	0.32	D<0.01
P. libanotica	0.78a	0.67a	1.00a	1.56a	0.34	ns
S. siberica	0.44a	0a	0.78a	0.89a	0.28	ns
S. tricolor	0b	0b	0.89a	1.44a	0.18	D<0.01
***T. bakeri* 'Lilac wonder'**	0.78a	0.33a	0.44a	0.33a	0.31	ns
T. clusiana* var. *chrysantha	2.56a	2.00a	2.11a	2.78a	0.21	D*C<0.01
***T. hageri* 'Splendens'**	0.11a	0.11a	0.67a	0a	0.23	ns
T. humilis	2.00a	2.33a	2.44a	1.89a	0.49	ns
T. kolpakowskiana	0.56a	0.11a	1.44a	0.67a	0.40	ns
T. linifolia	0.67a	1.00a	1.11a	1.89a	0.34	ns
T. saxatilis	0.67a	0.67a	0.67a	1.56a	0.33	ns
T. tarda	1.56a	1.33a	1.00a	1.00a	0.36	ns
T. turkestanica	2.11a	0.44b	3.00a	1.67ab	0.42	C<0.01
T. urumiensis	2.11a	1.78a	2.33a	2.44a	0.41	ns

Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other. SE= Standard Error, D=Depth of substrate, C=Covering plants, D*C=interaction between depth of substrate and covering plants

3.5 Summary of individual species

To make clear the potential of species for use in extensive green roofs, the emergence, plant growth, length of the period of above ground growth and flowering times and reproduction were summarized in Table 3.3.8. Geophytes on extensive green roofs should have high emergence and survival rate, sufficient foliage for healthy growth and flower growth for visual interest, and ideally good vegetative reproduction. In this study, it was found that *I. bucharica, M. azureum, T. clusiana* var. *chrysantha, T. humilis, T. polychroma, T. tarda, T. turkestanica, N. cyclamineus* 'February gold' and *T. urumiensis* fulfill this potential for extensive green roofs. In particular, *I. bucharica, M. azureum, T. clusiana* var. *chrysantha* and *T. humilis* showed good performance at the depth of 5cm. However, *N. cyclamineus* 'February gold' *and T. urumiensis* may require 10 cm for enough growth. The geophyte species which showed low emergence, small growth and no flowering were not recommended for use on extensive green roofs. They were *A. karataviense* 'Ivory queen', *A. ostrowskianum, C. sieberi* 'Tricolor', *C. tommasinianus, C. vernus* 'Vanguard', *I. danfordiae, I.* 'Mixture', *S. tricolor, T. bakeri* 'Lilac wonder', *T. hageri* 'Splendens' *and T. kolpakowskiana.*

Table 3.3. 8 Summary of performance of individual species

	Emergence	Growth	Length of the period of above ground growth	Length of flowering times	Reproduction	Potential for use on extensive green roofs
A. cernuum	Medium		Long	Short		
A. flavum	Medium		Long	Short		
***A. karataviense* 'Ivory queen'**	Low	Small	Short	Short		
A. ostrowskianum	High		Long	Short		
A. unifolium	Medium		Long	Short		
***C. sieberi* 'Tricolor'**	Low	Small	Short	NO		
C. tommasinianus	Low	Small	Short	NO		
***C. vernus* 'Vanguard'**	Low	Small	Short	Short		
I. bucharica	High		Long	Long	High	High
I. danfordiae	Low	Small	Short	NO		
I. reticulata	Low		Short	Short		
***I.* 'Mixture'**	High		Long	NO		
I. pallasii	Medium		Long	Short		
M. azureum	High		Long	Long		High
***N. cyclamineus* 'February gold'**	High		Long	Medium	High	High (10cm is recommended)
P. libanotica	Medium		Medium	Medium		
S. siberica	Low		Medium	Short		
S. tricolor	Medium		Medium	NO		
***S. tricolor* 'Mixed'**	Medium		Long	Short		
***T. bakeri* 'Lilac wonder'**	Low		Short	Short		
***T. batalinii* 'Bright gem'**	High		Long	Medium		
T. clusiana* var. *chrysantha	High		Long	Medium	High	High
***T. hageri* 'Splendens'**	Low	Small	Short	Short		
T. humilis	High		Long	Long	High	High
T. kolpakowskiana	Medium		Medium	Short		
T. linifolia	High		Long	Short		
T. polychroma	High		Long	Long		High
T. saxatilis	Medium		Medium	NO		
T. tarda	High		Long	Medium		High
T. turkestanica	High		Long	Medium		High
T. urumiensis	High		Long	Medium	High	High(10cm is recommended)
T. wilsoniana	High		Long	Short		

Emergence: Mean percentage of emergence plants per plot, 0≤Low≤30, 30<Medium≤70, 70<High
Growth: Small=small size
Length of the period of above ground growth (week): 0≤Short≤3, 3<Medium≤6, 6<Long
Length of flowering times (week): NO=no flowering, 0≤Short≤1, 1<Medium≤2, 2<Long
Reproduction: High=high shoot number in the second year

4. Discussion

4.1 Effect of depth of substrate

It was shown that the deeper substrates promoted greater emergence, growth, foliage and flower performance and reproduction in most of the geophyte species tested. Previous studies of plant selection for green roofs also showed that the plants performed better in deeper substrates, although the species used were not geophytes but other types of perennials such as forbs, grasses and *Sedum* spp. (Dunnett and Nolan, 2004, Dunnett, 2004a, Durham et al., 2007). In general, deeper substrates have the advantage of greater moisture retention and root protection from temperature fluctuations and allowed for more vertical space for plant roots to grow before reaching the root barrier (Durham et al., 2007). In particular, moisture retention seems to be important for plant growth; Dunnett (2004a) emphasized that the main limit to perennial plant growth on the extensive roof was water availability rather than depth of substrate on its own. However, it is important to notice the difference between geophyte species and other perennial species. Geophytic plants use stored biomass and water for early shoot development, air humidity or contact with water do not much affect the early stage of growth. Indeed, the previous experiment using *T. systola* showed the internal shoot development responded significantly to ambient temperature, but not to humidity, while foliage elongation outside the geophyte responded to variations in humidity but not to temperature (Boeken, 1991). Hence, it was considered that the water availability would be more important for later growth and flowering rather than the early stage of development.

The greater emergence in the deeper substrate in the second year suggested that the substrate depth might play an important role for survival rate over the winter. One of the reasons would be that there is less temperature fluctuation in the deeper substrate. Boivin et al. (2001) showed that the minimum daily temperatures were significantly lower at 5 cm plots (-0.4°C) than those measured at 10 cm (0.9°C) and 15 cm (1.6°C) depth on the extensive green roof in Quebec city Canada in October and November 1995. There have been few studies of the winter hardiness of geophyte species, but it was found that hardiness decreased in species of Tulip, Hyacinth, Narcissus and Iris, but in all species temperature below -1°C in the substrate had a harmful effect on foliage formation (Van der Valk, 1971). Generally, soil temperature would be not as low as 0°C in England, however, it was estimated that low temperatures in shallow substrates might affect the survival rate and growth of geophytes. Another advantage would be that the deeper substrate is more likely to protect the geophytes from digging by animals such as birds, mice and squirrels. It appears that there is a common problem with birds removing some of the plant, particularly plug plants in their search for foods on extensive green roofs (Emilsson and Rolf, 2005). Moreover, the emergence and the growth of geophytes in the first year may be less dependent on substrate depth than the second year, because the geophytes are able to use food reserves and growth laid down in the nursery, where growth conditions where presumable ideal. On the contrary, in the second year, food reserves and size of bulbs are much more likely to be determined by in-situ growing conditions (Dunnett, personal communications). *A. flavum, A. unifolium, A. cernuum, P. libanotica and I. reticulata* showed significantly higher emergence in the shallow substrate than in the deep substrate in the first year. This may be related to the requirement of low temperature for germination and the shallow substrate in lower temperature affected positively in the first year since they had higher temperature as usual in the first winter (Fig.3.3.8). The similar tendency was observed in *Allium ursinum*. The development of leaves of *A. ursinum* is strongly influenced by the temperature. At 4 °C for 1 month, the leaves remained within the bulbs and a transfer to 18 °C/10 °C at night did not promote any further growing the following 3 months. However, only after a cold treatment at 4 °C for 3 months was good leaf growth and inflorescence development achieved (Ernst, 1979).

For the geophytes which were used in these experiments, clonal growth appeared to be more important than seed reproduction. The seeds of *Allium* spp. germinated in the second year, however, most of the seedlings disappeared as time passed. Clonal growth is commonly stimulated in geophytes under the conditions in which there is a high assimilation rate (Van der Valk and Timmer, 1974). In deep substrates, plant growth was encouraged and a assimilation rate was higher than one of shallow substrate and it resulted in more reproduction. However, some studies showed that environmental stress such as shallow position in substrate (Barkham, 1980a), or as a result of high density (Barkham, 1980b) can bring about a high rate of geophytes' vegetative reproduction (Rees, 1972, Grime, 1977).

4.2 Effect of covering plants

Results showed that covering by *Sedum* did not have a significant effect for the emergence, the growth, the foliage and flower performance and the reproduction in most of the species. This might suggest that geophyte species may not compete much with *Sedum*. Generally, plants compete for water, light, mineral nutrient, and space. However, it might be possible that the geophyte species studied compete less for these with *S. album*. *Sedum* spp. use little water due to Crassulacean Acid Metabolism (CAM), which is the mechanism that open stomata at night therefore minimize the amount of water lost per amount of carbon dioxide into sugars through photosynthesis. Berghage, et al. (2005) showed that *S. album* and *Delosperma nubigenum* had a water loss rate during the first 3-5 days after irrigation (rain) following classic evapotraspiration models. After 4-10 days water loss rates slows, showing potential CAM activity and also often showing plant water gain from the atmosphere. *Sedum* spp. require little nutrient as well; nutrient needs are met partly by dust failing from the atmosphere and partly by the decomposition of dead plant material (Dunnett and

Kingsbury, 2004a). They have a creeping habitat and fibrous roots and they may not complete light and space much with geophytes.

Moreover, the total emergence was higher with *Sedum* in both substrate depths although there was no significant effect (Fig.3.3.11). Especially, covering plants seemed to be important for shallow substrate in emergence and growth. It was suggested that the covering of *Sedum* worked as a protection layer; it might play a similar role to a deeper substrate. They both prevent moisture evaporation and digging by animals and give some support to the geophytes. In the previous green roof study, it was shown that the substrate moisture levels of the vegetated treatments by *Sedum* were typically higher than those of unvegetated treatments in respective substrate designs, probably due to the shade provided by the plants canopy which lowered substrate moisture evaporation (Van Woert, et al., 2005). Therefore, the water availability might be slightly higher with *Sedum* spp. in this study as well. Mathew (1997) mentioned about the benefits of using creeping or carpeting plants with geophytes that the flower stems of the geophytes receive some support and the blooms are to some extent protected from soil splashes during heavy rain. The effect of covering plants was different from species to species. Some species, such *as A. flavum, A. ostrowskianum, I. reticulata* and *T. turkestanica* showed better emergence with *Sedum*, whereas the emergence of *T. uniflora* was restricted with *Sedum*. In growth, *T. kolpakowskiana* and *T. turkestanica* performed significantly better with *Sedum*, although *S. tricolor* showed the better performance without it. Probably the species, which showed a negative response with *Sedum* spp., might be more sensitive for competition with other species.

4.3 Individual species performance

From this study, it was shown that *I. bucharica, M. azureum, T. clusiana* var. *chrysantha, T. humilis, T. polychroma, T. tarda, T. turkestanica, N. cyclamineus* 'February gold' and *T. urumiensis* would have potential for extensive green roofs. Particularly, *I. bucharica, M. azureum, T. clusiana* var. *chrysantha* and *T. humilis* showed good performance in the depth of 5 cm, although they showed significantly better growth, foliage and flowering times in 10 cm. These species are probably drought tolerant and they are able to withstand high levels of temperature fluctuation. They could be very useful plants for extensive green roofs since few species can survive, grow and flower at the depth of 5 cm. On the contrary, *A. karataviense* 'Ivory queen', *C. sieberi* 'Tricolor', *C. tommasinianus, C. vernus* 'Vanguard', *I. danfordiae, T. bakeri* 'Lilac wonder' and *T. hageri* 'Splendens' were least successful. *A. cernuum, C.*

sieberi 'Tricolor', *C. tommasinianus, I. danfordiae, I.* 'Mixture', *S. tricolor* and *T. saxatilis* did not flower at all. Several reasons for this failure could be considered. This may indicate that the quality of these bulbs was a major likely effect on the outcome of the bulb assessment experiment. In addition, the fact that planting was delayed and the geophytes had been stored at room temperature for a long time might also have affected and these two factors might be the main reasons for unsuccessful of these species. Another reason would be that the geophytes might not able to emerge and grow because of low soil water availability or low nutrient. Moreover, they could not survive or continue their summer resting stage because conditions that trigger development were not met. Interestingly, the late flowering species are not very successful and they are short flowering. This may be related to the weather in Sheffield; generally, the rainfall is low in June (Fig.3.3.8). Generally, it is believed that *Crocus* spp. have potential for use in extensive green roofs. However, *Crocus* spp. did not show good germination, growth and flower performance, probably because they require cooler environments (they are often found under deciduous trees) and they may be not able to adapt to the green roof.

4.4 The selection of experimental site

In this study, the planting of Experiment 1 was delayed until January although the appropriate timing for geophytes was October and November. Therefore, two experiments were carried out because the planting season might affect significantly the geophyte growth. The reason of the delay was because of a limitation in the roof of commercial building and it there was a lack of flexibility and freedom compare to roofs at the University of Sheffield. It tends to be very difficult to find experimental sites and to carry out experiment on the roofs in the UK mainly due to the health and safety rules, although it seems these largely depend on the building owner's policy. In addition, if the green roofs are installed by the students and not by green roof companies, it would be problematic for getting materials, storage, carrying substrate and gathering the workers as well as the access and safety on the roof.

Generally, major green roof research is being carried out within a university or institution site (e.g. University of Applied Sciences Neubrandenburg in Germany, Michigan State University, Pennsylvania State University in the US, Augustenborg Botanical Roof Garden in Sweden), although it is common to use commercial buildings for spontaneous fauna and flora studies (Koehler, 2003, Brenneisen, 2003, Gedge, 2005). Results from experiments on roofs could be more convincing for green roof studies, however, it may not be always necessary to use a roof because the microclimate of roofs will vary considerably (e.g. building height, exposure, shade, direction, the building is heated in the winter or not) their location and surroundings (e.g. city, country side, altitude, surrounded by buildings or forest). Indeed, plant selection studies for green roofs are carried out on the ground using platforms and trays in Michigan State University and Pennsylvania State University respectively. However, it may be important to choose a ground site which is similar to roof top conditions. Before starting an experiment, it is necessary to measure and compare the microclimate of the roof and ground. When green roofs are chosen as experimental sites, all possible limitations should be carefully considered for the good quality of research, especially for long term research.

5. Conclusion

It was concluded that geophytes could be used to create greater seasonal interest and improve the aesthetic quality of extensive green roofs. Deeper substrates promote greater emergence, survival rate, growth, foliage and flower performance and reproduction in most of the geophyte species studied probably because they provide the advantage of moisture retention, less temperature fluctuation and protect the geophytes from digging by animals. Covering plants, *S. album,* did not compete with most of the geophyte species probably because *Sedum* spp. use little water and nutrient, and they have creeping habitat and fibrous roots. Moreover, *Sedum* seemed to work as a protection layer and the overall emergence was encouraged with *Sedum*, especially in the shallow substrate. About half the species showed the better growth, flowering and regeneration with *Sedum* spp. *I. bucharica, M. azureum, N. cyclamineus* 'February gold', *T. clusiana* var. *chrysantha, T. humilis, T. polychroma* and *T. urumiensis* were successful for use on extensive green roofs in the UK. Particularly, *I. bucharica, M. azureum, N. cyclamineus* 'February gold', *T. clusiana* var. *chrysantha* and *T. humilis* showed good performance in the depth of 5cm as well. Unsuccessful species, which showed low emergence, insufficient growth or no flowering, were *A. cernuum, A. karataviense* 'Ivory queen', *A. ostrowskianum, C. sieberi* 'Tricolor', *C. tommasinianus, C. vernus* 'Vanguard', *I. danfordiae, I.* 'Mixture', *S. tricolor, T. bakeri* 'Lilac wonder', *T. hageri* 'Splendens' and *T. kolpakowskiana.* Finally, because of the various difficult experiences in the use of the roof of commercial building for this experiment, when the experiment site for green roofs is chosen, all possible limitations should be carefully considered to achieve the good quality of research. In this experiment, any information of environment was measured, however, the data collection of continuous moisture and temperature using data logger into the substrate would have been helpful to analyze the plant growth. The use of control pots with optimal compost or planting on the ground would have highlighted whether the unsuccessful species failed because they could not adapt green roof environment or whether the low quality of bulbs caused the failure. Continuation of this experiment is required to understand how geophyte performance would change over the time. Especially reduction of nutrients of the substrate over time may affect the plant performance.In a future study, the comparison of geophyte performance with and without supplemental watering is recommended. It is also recommended to study geophytes in a climate-controlled greenhouse to identify the importance of environmental factors such as temperature and watering.

Chapter 4 Plant physiological study

4-1 Amount of water runoff from different vegetation types on extensive green roofs: effect of plant species, plant combinations and plant structure

Abstract

Reduction of water runoff is one of the most important environmental benefits to encourage green roof instalment. However, the influence of different vegetations on the amount of water runoff is still not clear. This study was carried out to investigate whether different plant species, plant combinations and vegetation structure affects the amount of water runoff in a greenhouse, Sheffield, UK. 12 species were chosen from the three major taxonomic groups for extensive green roofs: forbs, sedums and grasses and four species were chosen for each taxonomic group. The vegetation combinations included 12 monocultures (*Armeria maritima, Leontodon hispidus, Prunella vulgaris, Silene uniflora, Sedum acre* 'Minor', *S. album* 'Coral carpet', *S. rupestre, S. spurium* 'Coccineum', *Anthoxanthum odoratum, Festuca ovina, Koeleria macrantha, Trisetum flavescens*) and 5 mixtures (composed of four forbs, four sedums, four grasses and all 12 species mixture). These vegetations were grown individually in flats containing 3cm of commercial brick based substrate. The water runoff from these vegetations was tested for two types of simulated rain, heavy rain (10mm/h) and light rain (5mm/h), in the greenhouse every week. There was a significant difference between vegetation type and the amount of water runoff; the grass species were the most effective for reduction of water runoff followed by forbs and sedums in the both types of rain. This result was partly related to the water retention ability of plants rather than the ability to splash more water. It was also shown that the size and structure of plants significantly influenced the amount of water runoff. The non succulent species, which have a funnel structure with a tall, large leaf surface and vigorous roots were able to reduce runoff more than the succulent species which have creeping, small leaves with many gaps with shallow roots. In the case of green roofs which only the most stress-tolerant of plants such as Sedums can survive, upright *Sedum spp.* could work better for reduction of water runoff rather than creeping and succulent types of leafy species. In this study, species richness did not affect the amount of water runoff significantly.

1. Introduction

1.1 Green roofs and water runoff reduction

The predominance of sealed surfaces in the urban environment causes rapid run-off and higher peak flows, which carry nutrients, silts, hydrocarbons, chlorinated organic and heavy metals from the surfaces of buildings and streets into watercourses (English nature, 2003). Green roofs can reduce both the quantity and rate of runoff. There are many advantages to this: reducing pressure on urban drainage systems, enabling ground water to be replenished, reducing flood risk, and reducing the cost of drainage schemes because using smaller bore pipes is possible (Dunnett and Kingsbury, 2004a). Integration of sustainable technologies such as green roofs and rain water storage facilities leads to a very fast pay-back of the invested money (Köning, 2004). Some big cities have developed policies for water management through green roofs. For example, Portland, Oregon, in the US requires that developers who create or change more than 500 square feet of impermeable surface must manage storm water onsite. Also, the area where zoning limits a building's height-to-floor-area ratio can increase this ratio if the design has green roofs (Liptan, 2005).

1.2 Previous research of water runoff reduction of green roofs

As a result of their water storing capacity, green roofs may significantly reduce the runoff peak of the most rainfall events. The reduction consists of 1) delaying the initial time of runoff due to absorbing of water in the green roof system, 2) reducing the total runoff by retaining part of the rainfall, 3) distributing the runoff over a long time period through a relatively slow release of the excess water that is temporary stored in the pose of the substrate (Mentens et al., 2006). Indeed, much research has shown that green roofs can significantly reduce the amount of water runoff. A German experiment showed that 45%-70% of rainfall could be evaporated over a year from the water runoff data of 11 extensive green roofs (Kolb, 2004). In an experiment at Augustenborg Sweden, water runoff reduction was 18-88% monthly and 49% on average during the year through August 2001 to July 2002 (Bengtsson et al. 2005). Both these studies indicated that the reduction of water runoff was better in the summer than in the winter because of higher evaportanspiration in the summer. The US research also supported the reduction of water runoff by extensive green roofs. 100% coverage of sedum vegetation significantly retained rainfall, compared to a substrate without plants, and a typical commercial roof with gravel ballast, 66%, 63% and 100% respectively in Michigan (Rowe et al.,2003). Villarreal and Bengtsson (2005) showed whether conditions were dry or wet affected the retention capacity of the Sedum green-roof. For a dry condition, between 6 and 12 mm of rain were required to initiate runoff, while for wet conditions the response was almost straight. The research was carried out using only Sedum spp. According to previous research, it is apparent that the amount of water runoff would be influenced by the green roof design. Substrate types and depth and roof slope may be important (Rowe, et al., 2003, Mentens, et al. 2003, Koehler, 2004a, Kolb, 2004, Hoffman, 2006). FLL (2002) showed that different vegetation with different depths of substrate showed different degrees of water retention, as shown in Table 4.1.1. However, there has been very little study into how different vegetation types affect the amount of water runoff.

Table 4.1.1. Mean annual water retention of different depth of substrate and vegetation. Source: FLL (2002).

Depth of substrate(cm)	Vegetation	Mean annual water retention (%)
2-4	Moss-Sedum	40
>4-6	Sedum-moss	45
>6-10	Sedum-moss-herbaceous plants	50
>10-15	Sedum-herbaceous-grass plants	55
>15-20	Grass-herbaceous plants	60

The following section of this chapter considers how green roof vegetation may influence the capacity of a green roof to reduce stormwater runoff.

1.3 The effect of vegetation types on the amount of water runoff

Plant species and community composition have not been considered in the hydrology of green roofs. There is little information about how different vegetations influence water runoff from green roofs, probably because the majority of water management research has been carried out in the field of engineering. It has been proposed that the type of vegetation could affect water runoff characteristics. The amount of water runoff could describe as this formula: Water runoff = Precipitation- (Interception + Retention+ Transpiration from plants + Evaporation from soil) (Koehler, 2004b). Interception, transpiration and retention might be different from plant species.

It is proposed that different types of vegetation could affect water runoff characteristics because interception, transpiration and retention might be different between different plant species. Clark (1937 and 1940) compared the interception of rainfall by prairie grasses, weeds and certain crop plants. It was concluded that low-growing or mat forming plants did not intercept as much rain as plants of greater height because of the smaller surface that was exposed. A dense cover of prairie vegetation forms a very effective series of screens upon which some of water may be caught and prevented from reaching the ground. For example, *Andropogon scoparius* showed 57 per cent interception, *Convolvulus arvense* and *Buchloe dactyloides* showed 17 per cent and 31 per cent respectively. Beall (1934) compared the penetration of rainfall through the canopy of a mixed soft wood forest (*Pinus strobus* and *P. resinosa*) and hardwood forest (*Fagus grandifolia, Acer saccharum* and *Betula lutea*). The softwood forest showed 20 per cent greater interception compared to hardwood forest although having a nearly equal density of canopy. This may because soft wood species generally afford a much greater number of sharp angles and small rounded surfaces than do hardwoods, whereas the flat, smooth surfaces of hardwood leaves and twigs shed the droplets readily. Most of the intercepted water is re-evaporated and there is a slight possibility of direct uptake of water by plant tissues (Penman,1963).

The ideal plants for water management may have higher transpiration rates. There are three types of plants in terms of their photosynthetic mechanism, C3 plants (majority of plants belong to), C4 plants (mainly grasses) and CAM (Crassulacean Acid Metabolism) plants (mainly succulents). The transpiration / photosynthesis ratios (grams water transpired/ gram CO_2 fixed) are about 50-100 in CAM plants (in CAM mode), 250-300 in C4 plants and 400-500 in C3 plants (Edwards and Walker, 1983). This means that water use efficiency is the highest in CAM plants, followed by C4 plants and C3 plants. CAM plants are drought-tolerant, however, C3 plants or C4 plants might be better for water management under more favourable conditions. Desert plants tend to reduce their transpiration when the soil is dry. Reductions in transpiration during rainy and dry seasons are different in different species. For example, *Nitraria retusa* reduced its transpiration in the dry season to 78% of that in the rainy season, whereas *Noaea mucronata* reduced it by as much as 18% (Larcher, 2003). For both a reduction of the amount of water runoff and good survivability in the dry conditions of green roofs, ideal green roof plants would show higher transpiration in wet season and reduce in dry season.

Increased water retention in the soil will further reduce water and a reduction in the dry season. Root growth which opens up the soil structure, or mat forming plants such as grass species result in increase infiltration capacity (Morgan, 1980, Larcher, 2003). It is possible that vegetations with dense roots might be able to reduce water runoff more than vegetation with fine roots. Indeed, replacement of native vegetation with relatively shallow-rooted annual crops has resulted in greater water runoff in several parts of the world (Gregory, 2006).

1.4 The effect of vegetation diversity on the amount of water runoff

As well as the characteristics of individual plants, how might vegetation diversity as a whole influence the hydrological performance of green roofs? This question can be partly answered using ecological theory. Many experiments have indicated there is a positive relationship between plant species richness and ecosystem functioning, especially productivity. Some of them have concluded that increasing species richness allows a greater chance of enhanced productivity (eg. Naeem et al., 1994). Productivity could influence green roof hydrology in the following ways. 1) The more complex architecture of the high diversity plots slows down the rate at which water hitting the top of the canopy reaches the soil and increases the amount absorbed by plants and soil (Rixen and Mulder, 2005), 2) Multi-layered vegetation might cover the bare soil, thereby reducing the amount of water which reaches to the ground (Solbrig, 1994), 3) The maintenance of higher subcanopy humidity by species in dense vegetation (Mulder et al. 2001) 4) Different species may have different peak of growth and reproduction, which would cause different water harvesting ability (Solbrig, 1994). Because of these reasons, it might be supposed that water runoff could be reduced if the vegetation contains many species and a variety of structural types.

1.5 The effect of different types of green roofs on the amount of water runoff

It is also probable that different types of green roofs may work differently in terms of reduction of water runoff. There are several types of extensive green roofs, such as monoculture green roof, brown roofs, dry meadow green roofs, semi-extensive green roofs and wetland green roofs. For example, brown roofs (using native species, local plant communities and local soils) which are generally aimed at creating habitat for biodiversity, may also work well for reduction of water runoff. At present, however, there is no research to show this. The amount of water runoff is influenced by various factors, such as plant selection, substrate type, planting design and plant density. There is little comparative study to prove this and further research is necessary.

1.6 The effect of different types of rain on the amount of water runoff

The amount of water runoff could also be affected by the type of rain. The percentage of interception may be high during showers of low intensity, the amount of water held on the plants may not satisfy their storage capacity. During normal rainfall of long duration, a large percentage of the moisture will reach the ground (Clark, 1940). MacMillan (2004) studied the water runoff from wildflower green roofs and concluded that the peak flow reduction decreases with larger storm events. Storm ranging in sizes from 10-19mm. 20-29mm, 30-39mm, and ≥40mm had an average peak flow reduction of 85%, 82%, 68%, and 46% respectively.

1.7 Previous study of the effect of different vegetation types on water runoff in ecosystem function

The experiment reported here was based on a previous study of the role of diversity in the maintenance of community and ecosystem function. In the previous study, the effect of different vegetation types with contrasting architecture on water runoff was investigated. An experiment was established in 1997 in the experimental garden of the University of Sheffield to investigate the effect of different vegetation types with contrasting architecture and growing in shallow, free draining substrates, on runoff quantity and quality. The original aim of the experiment was to determine the effect of plant diversity on ecosystem properties. However, the experimental design, in effect, created a series of green roofs, and therefore the results are highly applicable in this context. A system of 'microcosms' (small, self contained artificial plant communities) and lysimeters (apparatus for collecting run-off) was constructed, consisting of trays with dimension 60 x 60 x 15 cm deep from black polypropylene plastic. All joints were welded for strength and water-tightness. Forty-one 1.2 cm diameter holes were drilled in each base for free drainage, and a semi-permeable geotextile mat layed over the base to retain the soil. A hopper unit constructed as an inverted pyramid with a central outlet pipe was attached beneath each tray using waterproof sealant. Each unit drained into a 25 litre collection vessel that had been marked with a graduated scale and then painted to reduce light transmission and reflect radiant heat. The trays were supported in rows 1.5 m above the ground allowing easy access for monitoring, and room beneath for the collection vessels. The trays were planted with species from a species-rich calcareous grassland growing on a thin 'rendzina' soil (free-draining soil with a high mineral content) over limestone bedrock in the Peak District National Park, near Sheffield. The trays were filled to a depth of 1 cm with the rendzina soil and trimmed cuttings of the plant species were inserted according to a pre-planned planting map, at 10 cm apart, in late autumn and winter of 1997. Weeding was carried out throughout the experiment to maintain initial species composition. Supplementary watering was applied during exceptionally dry periods to avoid severe droughting (Dunnet et al, 2005). The vegetation types used were three monocultures (*Festuca ovina*, *Carex flacca* and *Leontodon hispidus*) and five mixtures (composed of four grasses, four sedges, four forbs, the monoculture species in combination and all twelve species respectively). The twelve species were *Festuca ovina*, *Helictotrichon pratense*, *Koeleria macrantha*, *Briza media*, *Carex flacca*, *Carex panicea*, *Carex pulicaris*, *Leontodon hispidus*, *Succisa pratensis*, *Viola riviniana*, *Campanula rotundifolia*, and a Bryophyte. The monoculture of *L. hispidus* and the bare soil treatment both had less percolate than that of the twelve species mixture. The water runoff amount was different by species by species, however, the results showed that no consistent relationship between species richness of the synthesised communities and the volume of percolate collected (Booth and Grime, 2001, Dunnet et al, 2005). Although this ecological study provided useful information for green roofs, it was necessary to confirm the result using green roof plants and substrate. The substrate used was a natural soil and not a synthetic green roof substrate and therefore may have different drainage properties, in particular because of a higher organic matter content than might normally be encountered in a green roof substrate (Dunnet et al, 2005). In addition, to investigate the relationship between the amount of water runoff and vegetation more precisely, simulated rainfall was used in the green house for this experiment.

1.8 Research questions

This experiment described below aimed to answer the following questions:

1) Do different plant species and plant combination influence the amount of water runoff from green roofs?
2) Which types of vegetation perform best for water runoff management?
3) Is the relationship between the amount of water runoff and vegetation composition different depending on rainfall intensity?
4) Is there any relationship between the amount of water runoff and the amount of water retained by the green roof?
5) What kind of plant structure could best reduce water runoff ?

2. Materials and methods

This experiment involved the application in an experimental greenhouse of simulated rain at different intensities to green roof vegetations of differing diversities, and was modelled on a study of the role of diversity in the maintenance of community and ecosystem function (Booth and Grime, 2001, Dunnett et al., 2005), using a different selection of plants, substrate type and experimental site. The gradient of diversity was created by choosing 12 different and contrasting species to make the different vegetation types. These species were chosen from the three major taxonomic groups used for extensive green roofs: forbs, sedums and grasses. Four species that are used in extensive green roofs were chosen from each of these taxonomic groups. The combinations increased in their diversity: from simple monocultures, 4 species mixtures and 12 species mixtures. The combinations were; 12 monocultures (*Armeria maritima, Leontodon hispidus, Prunella vulgaris, Silene uniflora, Sedum acre* 'Minor', *S. album* 'Coral carpet', *Sedum rupestre, Sedum spurium* 'Coccineum', *Anthoxanthum odoratum,* *Festuca ovina, Koeleria macrantha, Trisetum flavescens*) and 5 mixtures (composed of four forbs, four sedums, four grasses and all 12 species mixture). *L. hispidus, F. ovina K. macrantha* were used in the previous study by Booth and Grime (2001). *L. hispidus, P. vulgaris*, and four grass species can be found in limestone grasslands. *A.maritima, S. uniflora* and four Sedum spp. are commonly used for green roofs. These plants have different leaves types, roots structures and habitats. Their characteristics are summarized below.

Table 4.1.2. The characteristics of 12 species (from Brickwell, 2003, Hubbard, 1984, Snodgrass and Snodgrass, 2006)

Plant name	Plant type	Leaves	Roots
A. maritima	Forbs	Dense rosettes of liner to sharp shaped leaves	Shallow roots
L. hispidus	Forbs	Erect or oblique usually branched premorose stock. Hispid with forked hairs	Root stock with shortly cylindrical
P. vulgaris	Forbs	Broadly ovate, spreading and vigorous growth	Rooting freely from nods.
S. uniflora	Forbs	Fleshy, lance shaped leaves, fringed with hairs	Deep rooting
S. acre 'Minor'	Sedum	Erect or trailing stems densely clothed in overlapping, triangular leaves.	Fibrous roots.
S. album 'Coral carpet'	Sedum	Glabrous green, creeping stem forming large mats, small ovoid-globose to cylindrical leaves.	Fibrous roots.
S. rupestre	Sedum	Alternate, pointed, cylindrical leaves. Upright, leafy woody stems.	Fibrous roots.
S. spurium 'Coccineum'	Sedum	Upright, branching red stems bearing opposite, ovate, toothed leaves.	Developed root stocks.
A. odoratum	Grass	A tufted, culms erect or spreading, stout and smooth leaves.	Fibrous root. Relatively shallow root system.
F. ovina	Grass	Density tufted, culms erect or spreading, very slender, stiff, narrowly liner, inrolled, hairless smooth leaves.	Relatively shallow root system.
K. macrantha	Grass	Densely tufted, forming a compact mound of narrowly linear, hairy leaves.	Fibrous root system, when competing with other grasses, their roots are generally shallower.
T. flavescens	Grass	A loosely tufted, culms erect or spreading, slender, rather weak, unbranched, hairy near the nods.	A dense mass of fibrous roots, relatively unbranched upper parts, densely branched and with in lower.

This experiment was carried out in a green house of experimental garden, University of Sheffield, UK. The seeds of the forbs and grasses were obtained from Emorsgate Wild Seeds (Norfolk, UK) and were sown in plug trays on 5th March 2006. After germination, the plants were thinned to one plant in each plug cell. The *Sedum* spp. were obtained from The Alpine and Grass Nursery in Lincolnshire, UK. Leaf cuttings of the sedums were taken on 5th March 2006, and rooted in John Innes no.1 compost, again in plug trays, with one cutting per plug cell. These plug trays were placed in the greenhouse with no temperature control and they were watered every other day. The plug plants were transplanted into flats (36.8 cm x 21.6 cm x 5.7 cm) on 8th May 2006. The transplanting medium was a mixture of commercial green roof substrates: Zinco sedum substrate and Zinco semi-intensive substrate (1:1), which are based on crushed tile or brick. The organic matter content of the substrate mixture was 10-15 %. In each flat, 3000 g of substrate was used and 12 plants were planted. There were three replicates for each vegetation type. The vegetation types in the flats were monoculture (one species only in each flat, 36 flats in total) , forbs, sedums, grasses only, comprising 4 species of each plant type in each flat (9 flats in total), and the12 species mixture (3 flats in total), resulting in a grand total of 48 flats. The flats were watered every other day until the experiment started.

To apply the exact amount of artificial rainfall, a rain simulator was used (Figs.4.1.1-4.1.2). This rain simulator was made in the Department of Engineering, Sheffield University. It consists of a plastic tank (50.3 cm x 67.5 cm x 41.0 cm outside, 47.7 cm x 65.0 cm x 39.9 cm inside) with 7 x 10 rows of holes (diameter:5 mm), each with a needle attached (intervals of 4.8 cm) at the bottom. The tank was set up at 61.5 cm above the table. A sprinkler is often used for water runoff experiments, however, the needles were used in this experiment to produce irregular water drops, which were similar to real rain. To collect the runoff water, a flat without drainage holes was put underneath the vegetation flat. It is possible to adjust the rate of rainfall per hour to change the amount of water in the tank. The rainfall becomes heavier when the more water is put into the tank. The possible rate of rainfall is up to 10 mm/h and it is heavy rain which occasionally happens in England. The vegetation flat was raised above the water collection flat by 5cm so that the runoff water was separated from the vegetation flat. Two flats were set up at the same time for each simulated rainfall event.

The runoff from all the vegetation flats was measured every 7 days from 16th September 2006 to 3rd November 2006, giving a total of 12 weeks. There were two types of simulated rain fall: in the first six weeks a heavy rain was applied (10 mm/h) and in the second six weeks a light rain was applied (5 mm/h). For the simulated heavy rain, the tank was filled up to 39.0 cm and allowed to fall to a depth of 37.4 cm (2 L for each flat) and in the light rain, filled up to 22.8 cm and allowed to fall to 22.0 cm (1 L for each flat). This change in depth for both rainfall intensities lasted 15 minutes. After the rainfall was applied, the flats were left in place until no further water left the base of the flats into the collecting flat. The amount of runoff water in the flat was measured by transferring the collected water to a 200 mL graduated cylinder.

In addition, in the last two weeks, as well as measuring the water runoff from the heavy rain and light rain events, the total weight of the vegetation flats was measured before rainfall was applied, and then again after 15 minutes. This was done to evaluate the absorptive capacity of the different vegetation types, and to evaluate the rate of loss of water from the systems. The rate of increase weight was calculated by this formula: (Weight of flat after rain-initial weight of flat) /initial weight of flat x 100 (%). The greater the % increase, the greater the amount of water is retained in the system, rather than being leaked as runoff.

Except for the weekly artificial rainfall, no additional water was added. Plant growth, height, shoot number, diameter (average of length and width), was measured every two weeks. The growth of representative plants from each flat was measured to obtain three replicates of each species in total: one plant was measured for monoculture, four plants (one plant from each species) for 4 species mixture, and all plants for 12 mixture. The representative plants were marked and the same plant growth was measured.

After the experiment was complete all plants were harvested. The harvested plants were dried in the greenhouse until January 2007. Because of humidity in the greenhouse, the shoots were additionally dried in a desiccator for one week and shoot dry weight and root dry weight were measured. Analysis of Variance (Minitab Release 14) was used to detect vegetation effects. When there were significant differences, means were separated by a Tukey test. To investigate the relationship between the amount of water runoff and plant growth (Height and diameter), and the amount of water runoff and water retention, Analysis of Variance as well as regression were calculated (Minitab Release 14).

It was hypothesised that the ability of water capture of individual plant (how quickly drops flow from plant surface) could be important in reduction of water runoff. Therefore, water was dropped on to leaves of individual plants of each species from a 5 mL syringe, and the way in which water adhered to and fell from the leafs was observed. Results were classified into five classes: (1=Drops flow immediately, 2=Drops flow slowly, 3=Drops stay for a while and flow slowly, 4=Drops formed and stay on the leaf surface, 5=Drops have surface tension).

Fig.4.1.1 Overview of rain simulator

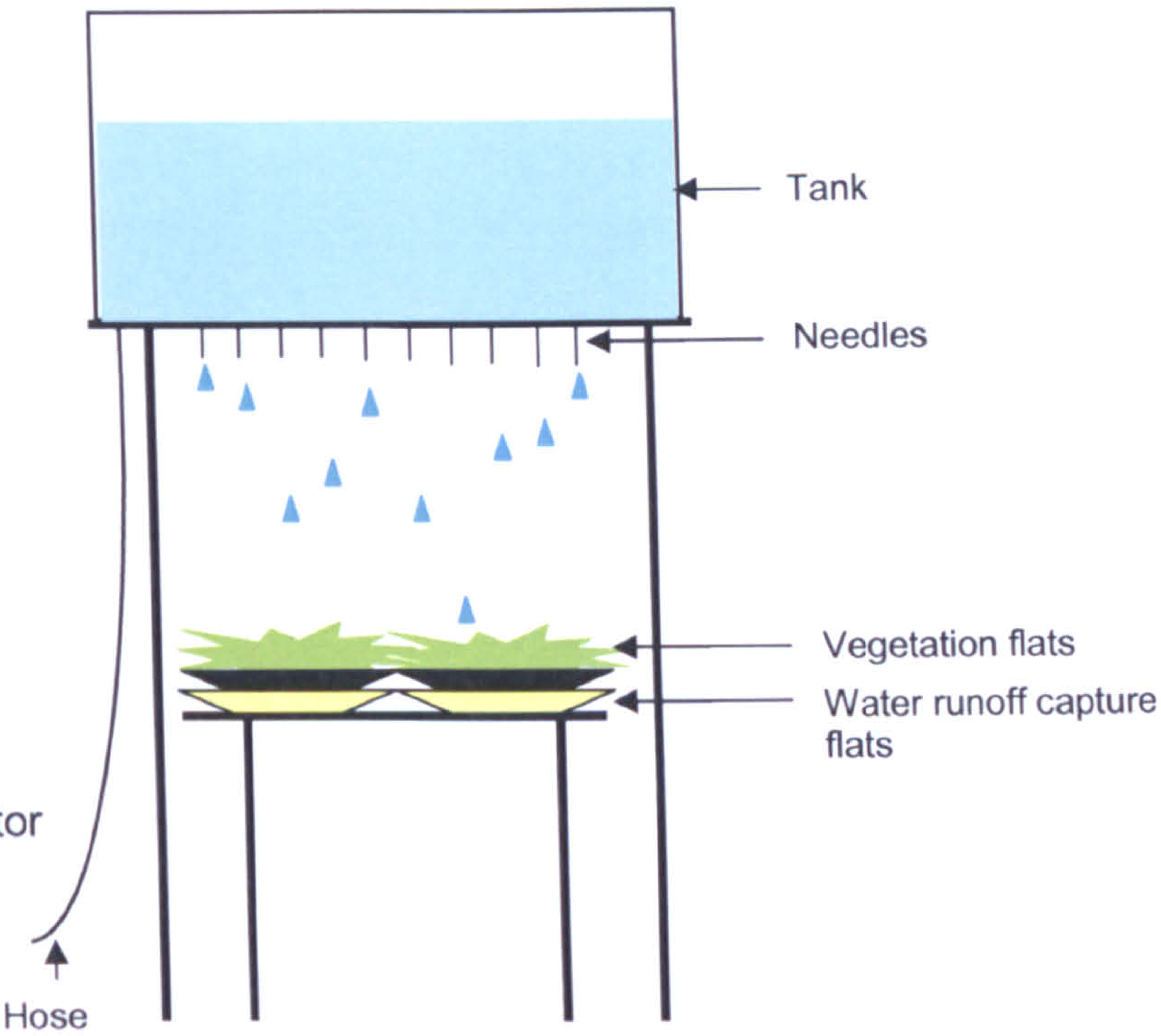


Fig.4.1.2 Rain simulator

Armeria	*Armeria*	*Armeria*
Armeria	*Armeria*	*Armeria*
Armeria	*Armeria*	*Armeria*
Armeria	*Armeria*	*Armeria*

1. Monoculture

Armeria	*Leontodon*	*Prunella*
Prunella	*Armeria*	*Leontodon*
Silene	*Armeria*	*Silene*
Leontodon	*Silene*	*Prunella*

2. 4 species mixture

S. acre	*Prunella*	*Trisetum*
Koeleria	*S. album*	*Armeria*
S. spurium	*Anthoxanthum*	*S. rupestre*
Silene	*Festuca*	*Leontodon*

3. 12 species mixture

Fig.4.1.3 The arrangement of plants within the flats
(Plants were randomly distributed in each replicate)

3. Results

3.1 The influence of the different vegetation types on mean amount of water runoff

Comparison of the amount of water runoff from heavy rain and light rain between the different vegetation types are shown in Fig.4.1.4 and Fig.4.1.5. Each figure was obtained from the mean of 15 measurements (3 replicates x 5 weeks). There was a highly significant difference between the amount of water runoff and the vegetation types. There was a similar trend for both types of rain; grass species were the most effective for reduction of water runoff followed by forbs and sedums. In monoculture, *A. odoratum* and *S. uniflora* reduced the amount of water to a greater degree that other species. Between forbs, *A. maritima* showed the largest amount of water runoff. Overall, *Sedum* spp. showed the larger amount of water runoff, although upright sedum species such as *S. rupestre* and *S. spurium* 'Coccineum' showed a rather small amount compared to the creeping species of *S. acre* 'Minor' and *S. album* 'Coral carpet' especially in the heavy rain. For the grass species, the density tufted species such as *K. macrantha* and *F. ovina* had more water runoff, although there was no significant difference between species.

The relationship between species richness and the amount of water runoff in the heavy rain was shown in Fig.4.1.6. There was not a significant relationship between them (y=1310-4.31x, P>0.05, R^2=0.20). The 12 species did not show the smallest amount of water runoff. Indeed, the water runoff from the monocultures of *A. odoratum S. uniflora T. flavescens* and the 4 grass mixture were smaller than 12 species mixture. For the 4 species mixtures, the grass mixture significantly reduced more rain water than the sedum mixture.

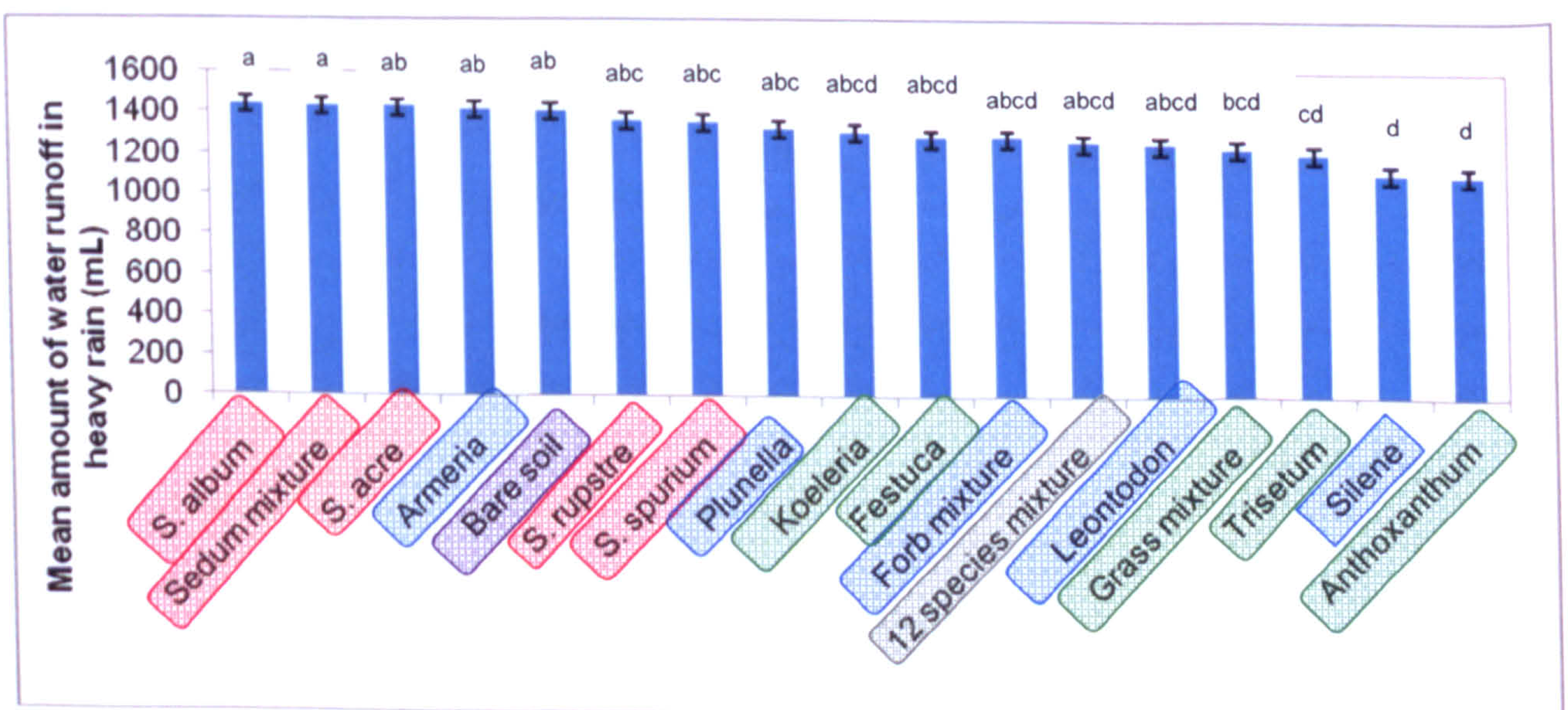


Fig.4.1.4 Mean amount of water runoff from different vegetation types in heavy rain Error bars represent standard error. Means with the same letter do not differ significantly from each other.

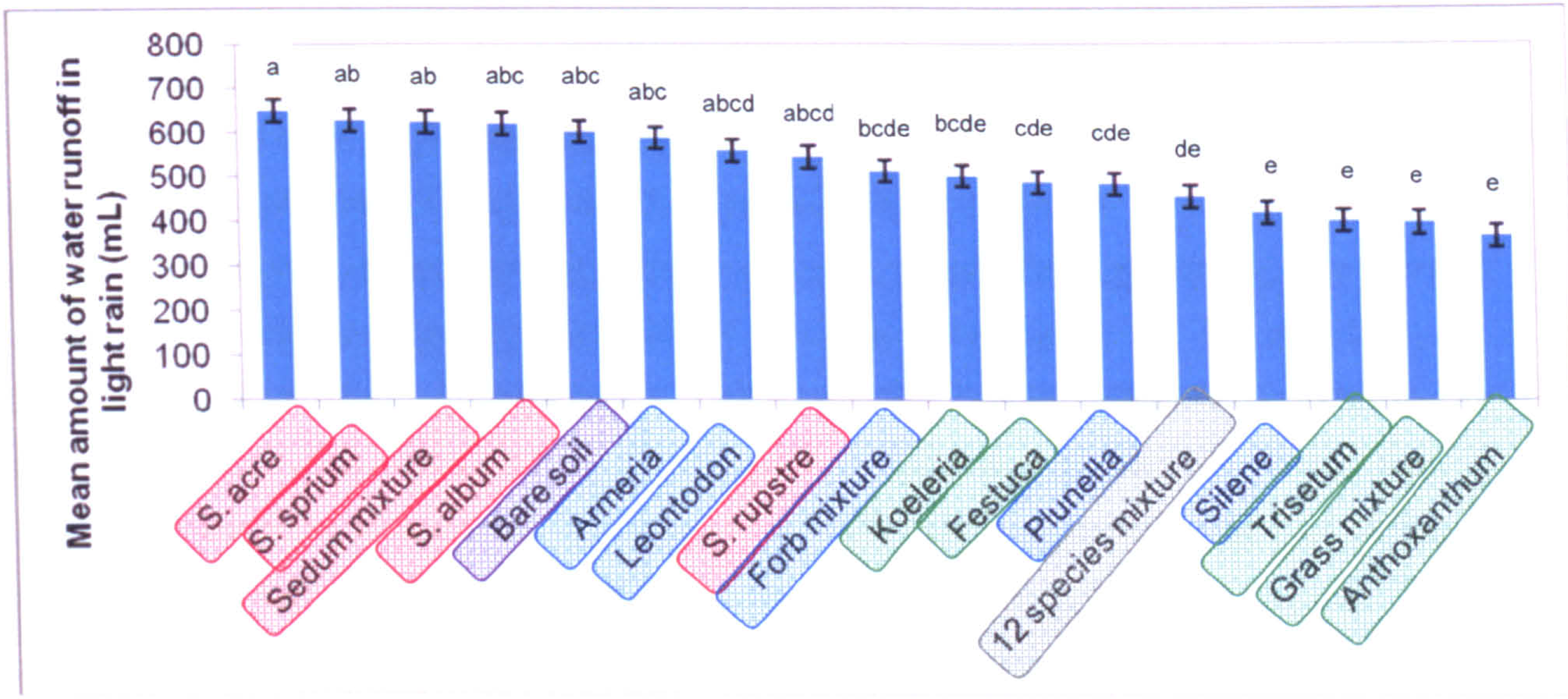


Fig.4.1.5 Mean amount of water runoff from different vegetation types in light rain Error bars represent standard error. Means with the same letter do not differ significantly from each other.

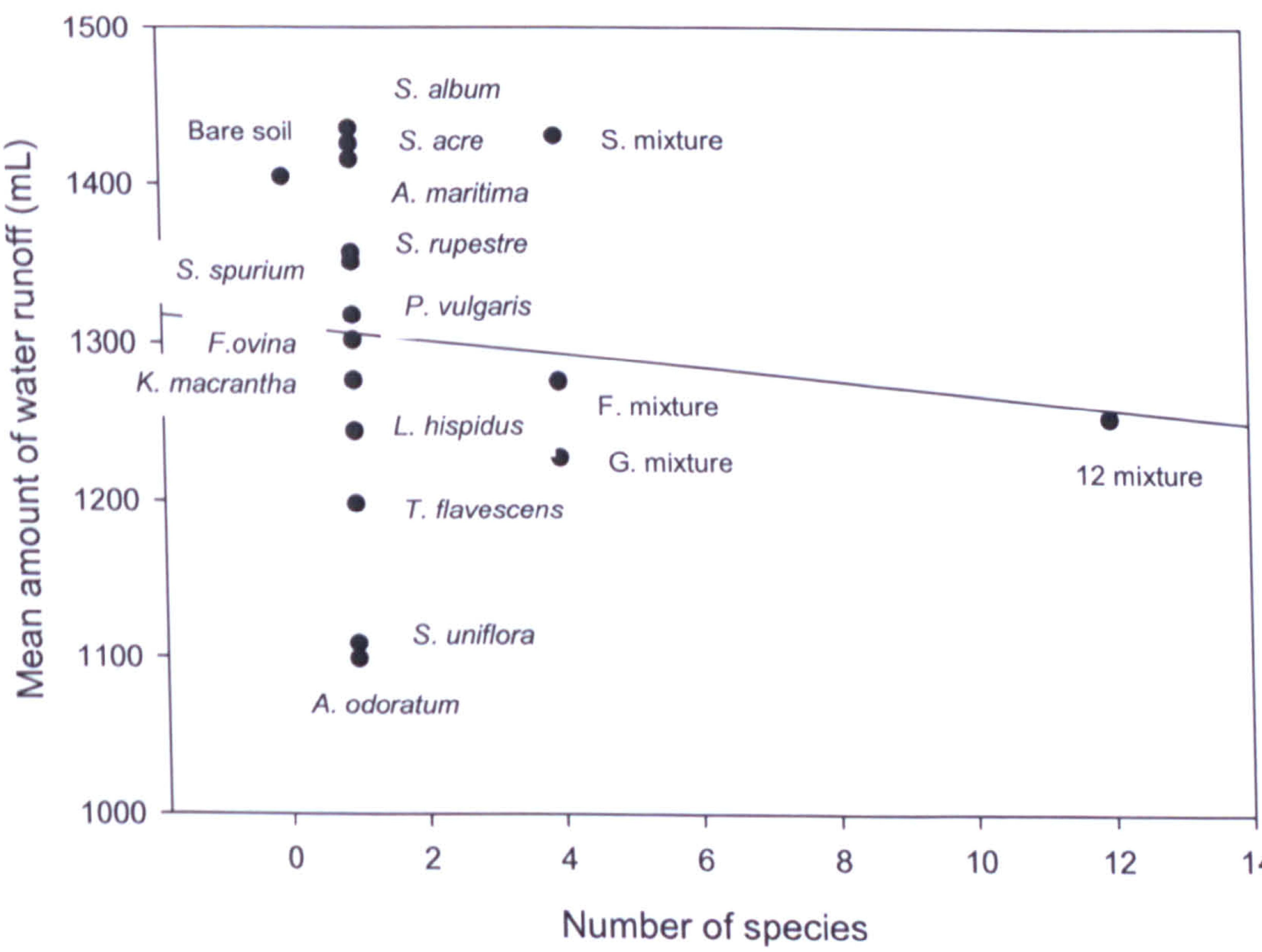


Fig.4.1.6 The relationship between species richness and mean amount of water runoff (mL) in the heavy rain (y=1310-4.31x, P>0.05,R^2=0.0%)

3.2 The relationship between rate of increase weight and mean amount of water runoff

It was demonstrated above that the different vegetation types affected the amount of water runoff. It was proposed that some vegetation types could catch or splash more water than other types. To confirm this, the relationship between the amount of water runoff and the rate of increase in weight of each vegetation type during the rainfall event. As it was mentioned, the rate of increase was calculated by this formula: (Weight of flat after rain - initial weight of flat) / initial weight of flat x100. The result from the heavy rain simulation on 3rd December is shown Fig.4.1.7. There was a significant negative relationship between amount of water (mL) and the rate of increase in weight (y = 1657-25.64x, $P<0.01$, R^2=41.5%). This result suggests that grass species very quickly absorbed water into the system compared to *Sedum* spp. where water was lost more quickly. For both heavy and light rain, the trend and statistical results were similar, therefore, only the result of heavy rain is shown. However, this trend was more clearly shown in the heavy rain.

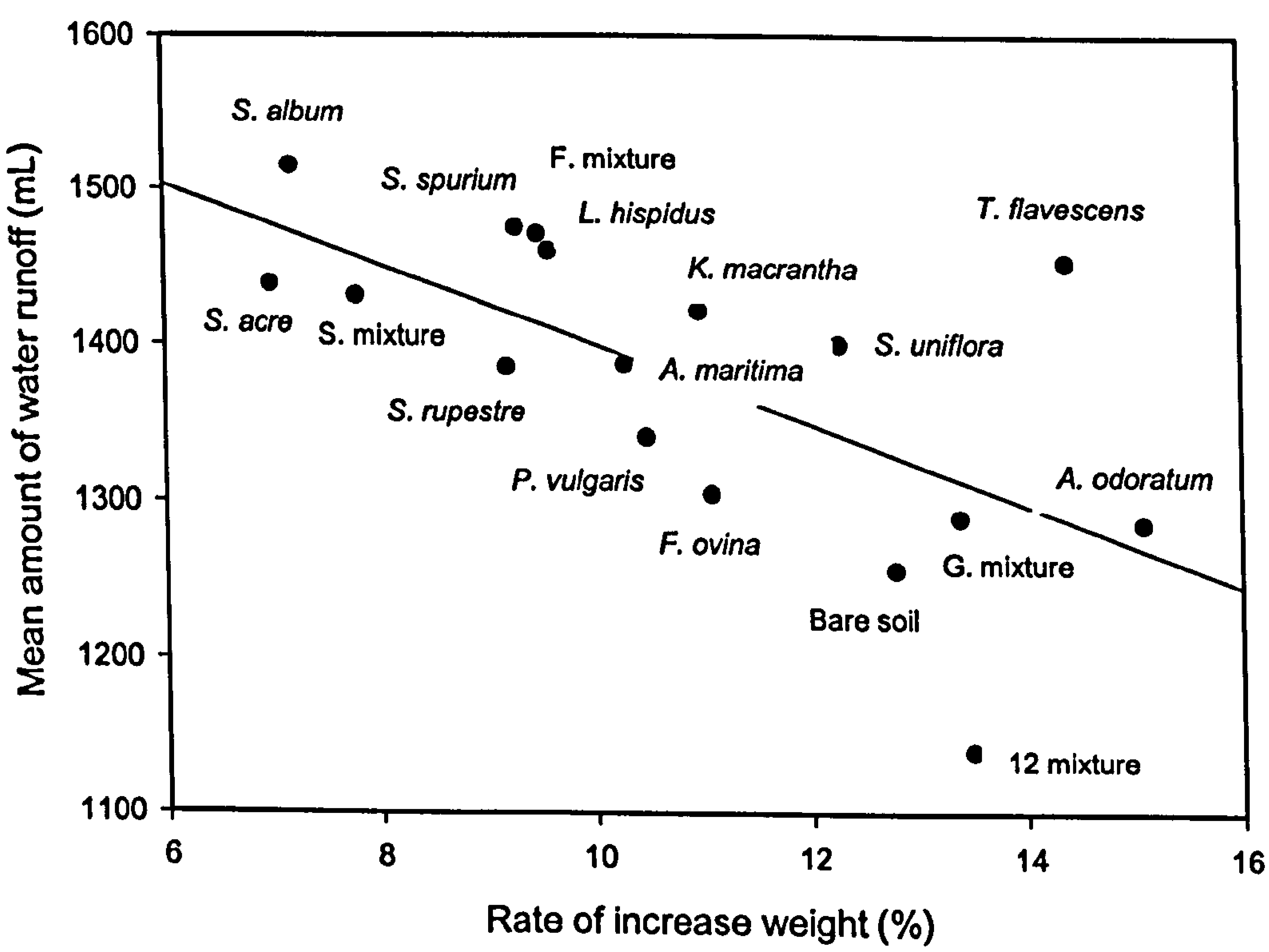


Fig.4.1.7 The relationship between rate of increase weight (%) and mean amount of water runoff (mL) in the heavy rain during the rainfall event (y=1657-25.64x,$P<0.01$,R^2=41.5%)

3.3 The relationship between plant structures and mean amount of water runoff

From the result in 3.2, it was shown that the vegetations which quickly absorbed water into the system may be able to reduce more water runoff. To study what kind of factor of plant structures could affect the capture of water, the relationship between amount of water runoff and plant structures (plant size, dry shoot weight and dry roots weight) were examined. In addition, the water capture of individual plant (How quickly drops flow from plant surface) was evaluated.

3.3.1 Plant size

The relationship between the amount of water runoff and plant size (Height and diameter) on 14th October 2006 is shown in Fig.4.1.8 and Fig.4.1.9 respectively. The results showed that the amount of water runoff was strongly related to plant size. There was a highly significant negative relationship between both height (cm) and diameter (cm) and the amount of water runoff (mL) (Height: y=1531-12.19x, $P<0.01$, R^2=53.2%. Diameter: y=1648-14.73x, $P<0.01$, R^2=57.8%). This indicates that species which have greater height and a larger diameter retain water to a greater extent than shorter species or those with a smaller diameter. Therefore, the majority of grass species, which have taller height and larger diameter, could reduce more water runoff than the majority of Sedum spp. which have creeping habitat with small spread. Plant growth was measured every two weeks, 5 times in total. Both of the relationships were compared each time and they showed the significant difference in all 5 measurements (result was not shown).

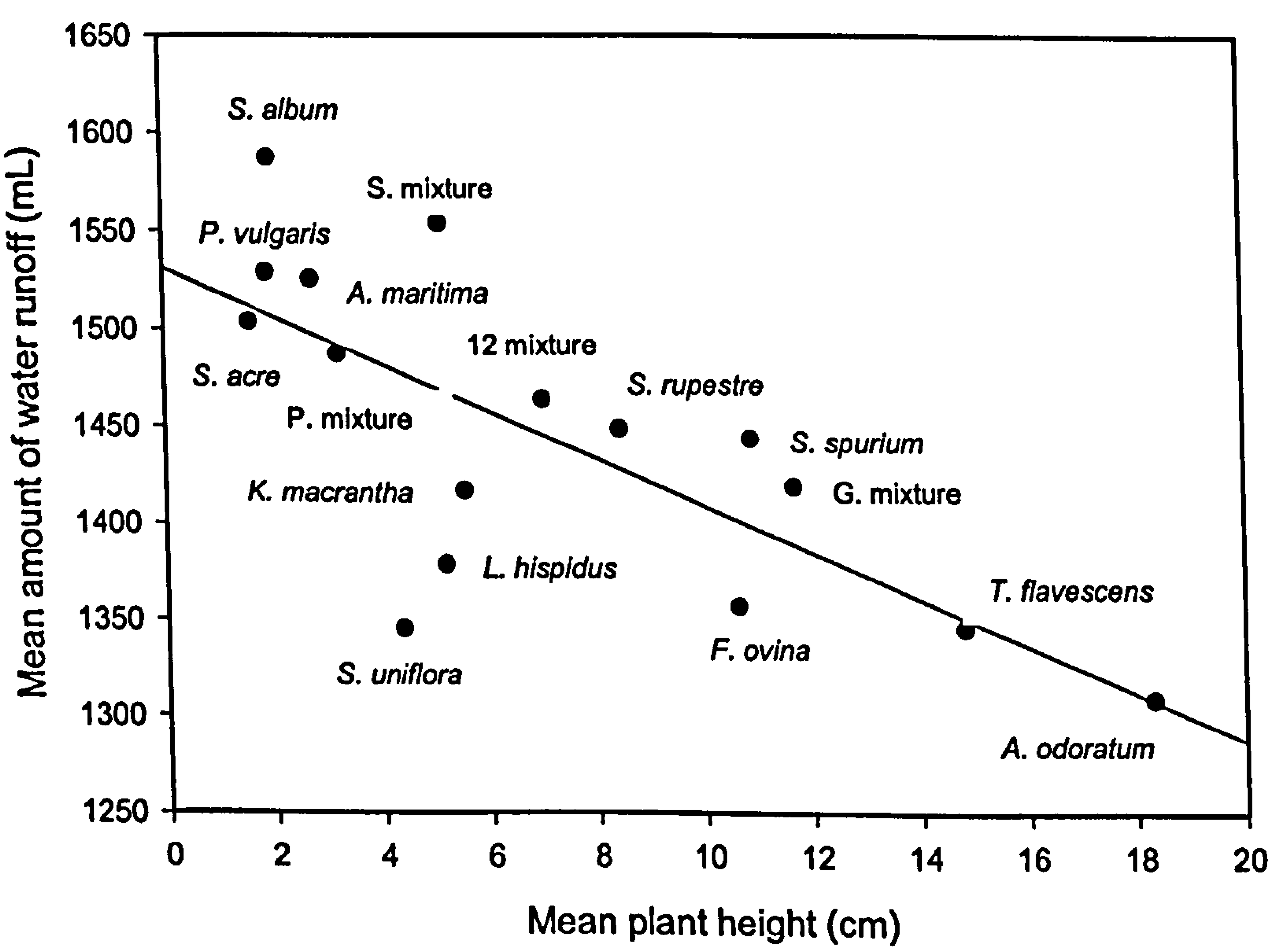


Fig.4.1.8 The relationship between mean plant height and mean amount of water runoff (mL) in the heavy rain (14th October 2006) (y=1531-12.19x, $P<0.01$, R^2=53.2%)

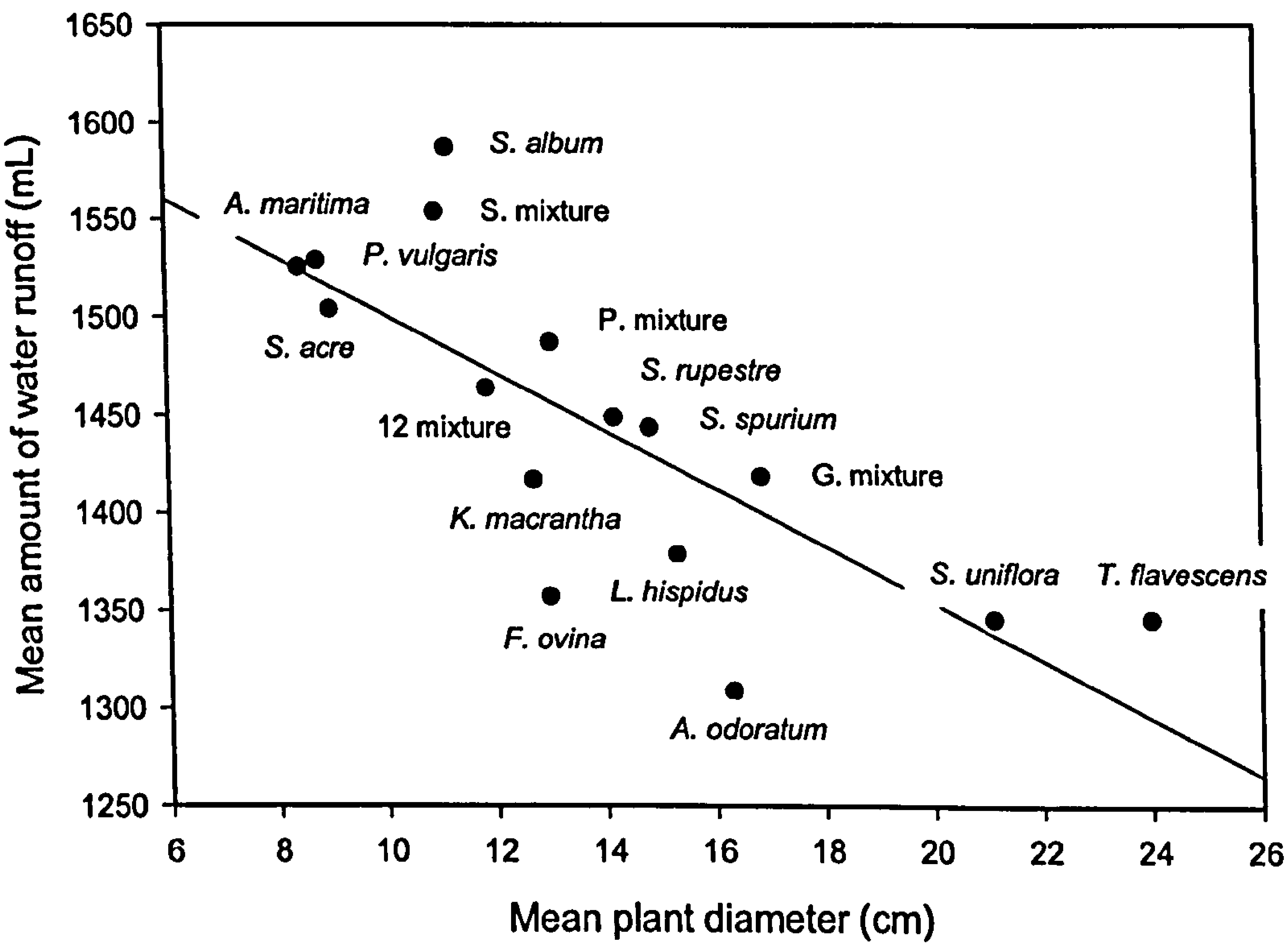


Fig.4.1.9 The relationship between mean plant diameter (cm) and mean amount of water runoff (mL) in the heavy rain (14th October 2006) ($y=1648-14.73x$, $P<0.01$, $R^2=57.8\%$)

3.3.2 The relationship between biomass and mean amount of water runoff

The results indicated that there was a significant negative relationship between mean dry weight of roots and the mean amount of water runoff in the heavy rain ($y=1370-132x$, $P<0.05$, $R^2=38.5\%$) (Fig.4.1.10). Same as above, this result suggests that dense roots, which generally grass species have, result in greater water capture in the soil. Interestingly, there was not a significant relationship between shoot dry weight and the mean amount of water runoff ($y=1318-27.47x$, $P>0.05$, $R^2=1.0\%$) (Fig.4.1.11). Therefore, plant structure appears to be more important for capture of water rather than total above- ground productivity.

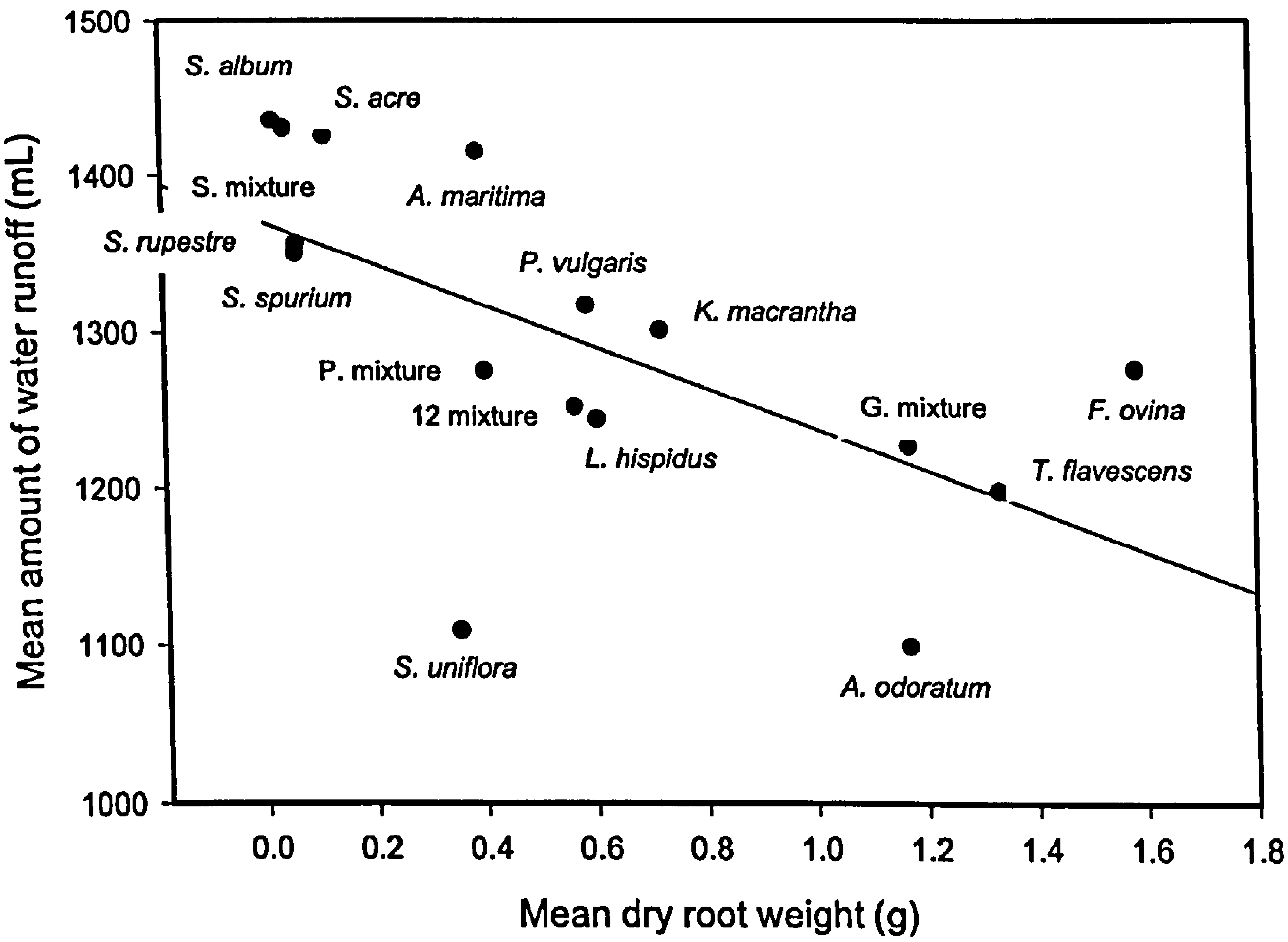


Fig.4.1.10 The relationship between mean dry root weight (g) and mean amount of water runoff (mL) in the heavy rain (y=1370-132x, $P<0.05$, R^2=38.5%)

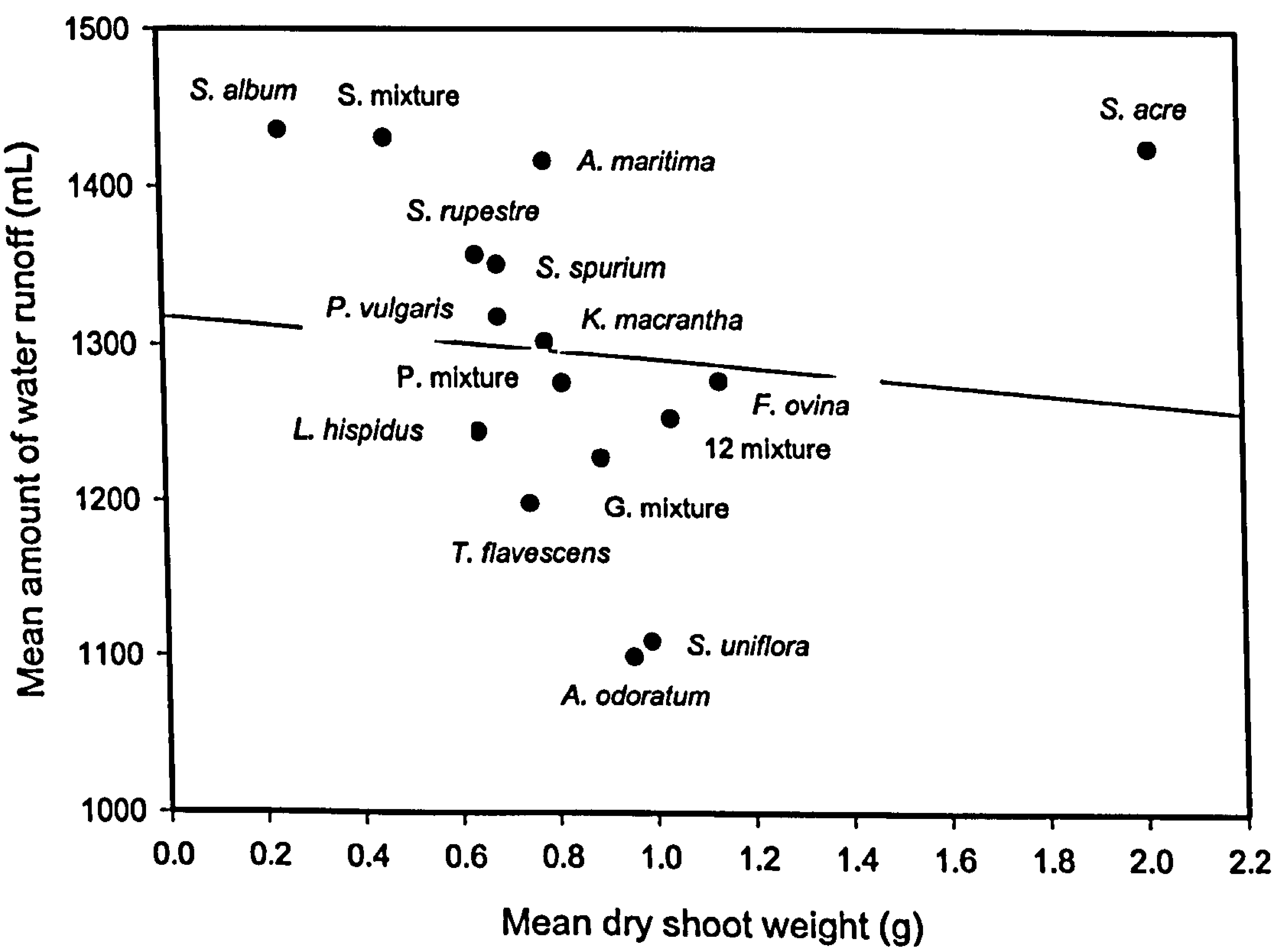


Fig.4.1.11 The relationship between mean dry shoot weight (g) and mean amount of water runoff (mL) in the heavy rain (y=1318-27.47x, $P>0.05$, R^2=1.0%)

3.4 The ability of water capture of individual plants

The ability of water capture of individual plant (how quickly drops flow from plant surface) is evaluated and shown in Table 4.1.3. According to observations by the author, the ability to capture or hold water was different between the plant species because of their different plant structures such as their surface, angle, and shape of leaves. The surface of *S. uniflora* is covered with a waxy cuticle and the plants have dense flat leaves. Water drops adhered to the leaves effectively. This is one of the reasons that *S. uniflora* was able to reduce the water runoff as much as the grass species. Hairy leaves such as *P. vulgaris*, *K. macrantha* and *T. flavescens* could catch more water drops than *F. ovina* which has needle-like leaves. Generally, water on the Sedum leaves dropped quickly, because of the small size of the leaves and the gaps between the leaves. However, the horizontal leaves of *S. rupestre* and *S. spurium* 'Coccineum' helped the water to stay on the leaves.

Table 4.1.3. The ability of water capture on the leaf surface

Plant species	Ability of water capture
A. maritima	2
L. hispidus	2
P. vulgaris	3
S. uniflora	5
S. acre 'Minor '	1
S. album 'Coral carpet'	1
S. rupestre	3
S. spurium 'Coccineum'	3
A. odoratum	4
F. ovina	2
K. macrantha	4
T. flavescens	4

(1=Drops flow immediately, 2=Drops flow slowly, 3=Drops stay for a while and flow slowly, 4=Drops formed and stay on the leaf surface, 5=Drops have surface tension)

4. Discussion

The result showed that the difference plant species and plant combination influenced the amount of water runoff, although there was no consistent relationship detected between species richness of synthesised communities and the amount of water runoff. This result was supported in a previous study by Booth and Grime (2001). They suggested that the lack of an observed consistent pattern of variation in water runoff related to either species richness or taxonomic type was probably related to the fact that data was collected over a period of relatively high rainfall in a geographical region which experiences quite high levels of precipitation. According to the study of Neath et al. (1991), differences in water retention have been correlated with differences in vegetation especially in areas subject to summer drought. There is the possibility that water runoff from the vegetation with greater species richness would be smaller than monocultures in the dry environment on the roofs when they are measured over the long term. Further detailed research is necessary to confirm this. There are good reasons to use diverse species mixes, apart from any hydrological advantages. Diverse mixtures may able to withstand disease, stresses including drought since they are more likely to contain that plants overcome them (Dunnett and Kingsbury, 2004a). A wider range of plants helps to avoid failure of establishment and maintenance and to cope with fluctuating environmental conditions (Vitousek and Hooper, 1994). Combining different species gives a dynamic aspect of visual by different structures and flowering time (Dunnett and Kingsbury, 2004a).

In this experiment, the general pattern of differences in runoff from plant species and plant combinations was the same as the study by Booth and Grime (2001), however, the detail of the result was different. Their result could be explained as follows. The mean amount of water runoff from individual plant combinations was in this order from small to large: bare soil, *L. hispidus*, 12 species, 4 sedges, 4 forbs, *C. flacca*, 4 grasses, 3 species and *F. ovina*. *F. ovina* was the only treatment significantly different from the rest of species in statistical analysis. A larger amount of water runoff from *F. ovina* was observed because of high rainfall and they have fine-leaved structure. The bare soil treatment showed the lowest amount of runoff. This may be related to ambient radiation raising the soil surface temperature and thus increasing evaporation loss. *L. hispidus* developed a very dense cover of foliage and the evaporation from the canopy and transpiration may have been relatively high in this species. These results were not observed in the current study. Water runoff from the bare ground was one of the highest amounts. *L. hispidus* did not show a particularly low amount of runoff and *F. ovina* also did not show a large amount. Probably this is related to the different type of rain (natural rain and artificial rain), and the differences between the sites (outside and green house) and the length and experiment (3 years and 3 months). These factors influence plant growth and evaportansipration, therefore, the amount of water runoff may be different.

The grass species were the most effective in reducing water runoff followed by forbs and Sedums. This could be explained by the water retention of plants. Grass species may be able to hold more water than *Sedum* spp. because they have a funnel structure with large leaf surface and vigorous roots. On the contrary, *Sedum spp.* tend to have small leaves with many gaps with shallow roots, which the water runs off rather quickly. It is interesting to note that *S. uniflora* could reduce runoff as much as the grass species. Clark (1940) observed the numerous small drops of water held on the stems of *Andropogon furcatus*, *Buchloe dactyloides*, and *Eragrostis ciliaensis*, and concluded that some water reached the soil by running down the stems but the amount appeared to be small compared with that dripping directly from the leaves. This might explain why the amount of water runoff from *S. uniflora* was smaller although even though they do not have the structure of tall and vigorous roots, they are still effective because the waxy and dense leaves could catch water.

Not only water capture, but also the water use of plants and water content in leaves may affect the amount of water runoff. Unfortunately, transpiration and stomata conductivity were not measured in this experiment. However, the larger amount of water runoff from *Sedum* spp. could be related to the low transpiration rate of CAM plants and high reserve water in leaves. In future research, it is necessary to compare the transpiration as well as water content in leaves between the plants which are commonly used in the green roofs.

In a previous water runoff study using *Sedum* spp. (Rowe et al., 2003), during rainfall events greater than 2 mm, there was no significant difference between the media only and sedum vegetation on roof sections, although during light rainfall events of less than 2 mm, vegetation did contribute to reducing water runoff. In this study, both heavy rain (10 mm/h) and light rain (5 mm/h) showed a similar trend for all results probably because the difference of the amount of rain was not enough. These experimental rainfall intensities were decided by the limitations of the tank and the time. It would be interesting to study further the various kinds of rain intensities, such as storm rain and misty rain, and short and longer rain events.

In this study, results indicated that grass species reduced water runoff more than *Sedum* spp. Therefore, is it always better to use grasses than sedums when water management is the main aim of green roof instalment? It is too early to answer this question since this experiment was rather intensive, carried out under artificial conditions and in a short time. In nature, air temperature, relative humidity, wind movements affect the interception of water through evaporation of moisture from plant surfaces (Clark, 1940). Moreover, water was used by plants at different times during the year, depending upon when they were growing and/or when water was available for use (Humphrey, 1959). It is necessary to investigate more plant species in diverse environments over a longer term, and to combine greenhouse and external studies to confirm the results reported here. As well as the hydrological benefits, the green roof environment such as the substrate depth, irrigation and microclimate should be taken account for plant selection. *Sedum spp.* are the most commonly used plants since sedums performed better than grasses in terms of its ability to withstand temperature and moisture extremes on extensive green roofs (Mather, 2006).

5. Conclusion

It was clear that the different vegetation types behaved differently for the reduction of water runoff. The grass species were the most effective for reduction of water runoff followed by forbs and sedums in the both types of rain. This result was partly related to plant structure: grass species have a funnel structure with large leaf surfaces and vigorous roots and were able to catch more water than the *Sedum spp.* which have small leaves with many gaps with shallow roots. In the case of green roofs where only the most stress-tolerant plants such as Sedums can survive, upright *Sedum* spp. could work better for reduction of water runoff rather than creeping and succulent types of leafy species. However, *Sedum* spp. are one of the most drought tolerant genera, therefore, it is necessary to consider about survivability of plants as well as their hydrological benefits. The results showed that species richness did not affect the amount of water runoff although the result might be different when the experiment was carried out in the longer term or outside. For further research, it would be necessary to combine the water runoff experiment in artificial conditions and the field, using both artificial rain based on patterns of real storm events and natural rain, and over the long term and short term. As well as the *Sedum spp.*, a variety of native and non-native plants should be investigated so that appropriate plants are selected for green roofs to achieve the benefit of reduction of water runoff.

4-2 Drought tolerance of different vegetation types in extensive green roofs: Effect of watering and diversity

Abstract

Plants for extensive green roofs must survive in a harsh environment. Because of their extreme drought tolerance, Sedum species are widely used for extensive green roofs. However, mixed plantings may be more advantageous over Sedum monocultures in terms both of aesthetic value and green roof performance e.g. creating habitats for biodiversity. Moreover, it might be expected that plant productivity, survival and the stability of green roofs would be affected by vegetation species richness and diversity. This experiment aimed at studying the drought tolerance of different plant species, plant combinations and plant diversities. 12 species were selected from the three major taxonomic groups used for extensive green roofs: forbs, sedums and grasses. Four species were chosen from each taxonomic group. The vegetation combinations included 12 monocultures (Forbs: *Armeria maritima, Origanum vulgare, Prunella vulgaris, Silene uniflora,* Sedums: *Sedum acre* 'Minor', *S. album* 'Coral carpet', *S. rupestre, S. spurium* 'Coccineum', Grasses: *Anthoxanthum odoratum, Festuca ovina, Koeleria macrantha, Trisetum flavescens*) and 4 species mixtures (composed of four forbs, four sedums, four grasses) and a mixture of a 12 species. These vegetations were grown individually in flats containing 3cm of a commercial bricked based substrate in a green house, Sheffield UK. There were three watering regimes: wet (water applied once a week), moderate (water applied once in two weeks), dry (water applied once in every three weeks). It was concluded that the forbs and grasses groups reached permanent wilting point after two to three weeks of no watering and they were not able to recover after they showed 50% desiccation. Forbs and grasses grew best in the once a week water treatment to maintain in visually attractive form. *Sedum* spp. was the most drought tolerant and except *S. spurium* 'Coccineum', they were able to survive well and maintain good visual quality even after three weeks of no watering. For the forbs and grasses, *A. maritima, K. macrantha* and *T. flavescens* were the more drought tolerant and showed higher survival. The striking result of this study was that overall survival increased as species richness increased, although the results of this experiment have shown no evidence of beneficial effects of increasing species richness on productivity. More than half of the species showed higher shoot biomass in monoculture than in mixture. This result suggests that diversity in vegetation reduces the vigour of potential dominant species. Root growth showed a greater positive response to species richness than shoot biomass in the condition of limited watering, probably because vertical separation of root systems could reduce interspecific

competition. Overall survival in 4 species was not as high as in the 12 species mixture and the growth in the 4 species mixture tended to be less than the monoculture and the 12 species mixture. It is likely that not only species richness but the combination of different functional plant species may affect the performance of plants.

1. Introduction

1.1 Characteristics of plants for extensive green roofs

Plants on extensive green roofs must survive in the harsh environment of a thin substrate, little water, temperature fluctuation, high wind, high radiation and limited root growth. Because of their drought tolerance, year-round good looks, ease of propagation and suitability for shallow substrate, *Sedum* spp. are widely used for extensive green roofs (Dunnett and Kingsbury, 2004a). Indeed, *Sedum* spp. have distinct advantages in dry environments because of their photosynthesis, Crassulacean Acid Metabolism (CAM) and storage of water in leaves. They show net CO_2 uptake from the atmosphere during the night to reduce the water loss. They also respond to drought by closing stomata to reduce water loss. Sedum spp. tend to have thick leaves and reserve water in the mesophyll of leaves. In rainy seasons, sap of these Sedums circulates vigorously, the chlorophyll is rejuvenated and growth proceeds. In dry months with high temperatures, they are dormant, slowly drawing upon stored reserves (Kluge and Ting, 1978). Many previous studies show that Sedum spp. can survive well under severe drought (Gurevitch, et al. 1986, Terri et al., 1986, Iijima, 2001). One study examined the drought tolerance of *Sedum* spp. and some perennials on extensive green roofs. Even after a 4-month period, *Sedum* spp. survived and maintained active photosynthetic metabolism to a greater extent than non-succulent species of *Schizachyrium scoparium* and *Coreopsis lanceolata*. Furthermore, when Sedum was watered after 28 days of drought, chlorophyll fluorescence values recovered to values characteristic of the 2 days between watering treatments. In contrast, the non-CAM plants required watering every other day to survive and maintain active growth and development (Durham et al., 2004). In some cases, hardy succulents such as Sedums might be the only choices for thin substrate, non-irrigated extensive green roofs (Snodgrass and Snodgrass, 2006). If green roofs have a slightly greater depth of substrate and/or the possibility of supplemental watering, the use of a wide range of species is recommended especially for the visible and accessible places (Dunnett and Kingsbury, 2004a).

1.2 Effect of plant species diversity

As it was introduced in Chapter 2, previous studies showed that water availability may be the key regulating factor for plant development on green roofs (Dunnett, 2004a, Koehler ,2004b, Monterusso, et al., 2005, Nagase and Thuring, 2006). However, the previous plant selection studies for green roofs focused only on individual plants - plant diversities were not addressed, although many green roofs include not only one species but several species.

Many previous studies showed that there is a positive relationship between plant species richness and ecosystem functioning. High species diversity may increase the productivity and stability of an ecosystem. This can be explained as follows. 1) In more diverse communities, differences between species (e.g. architecture) may allow complementary use of resources (light, nutrients, space, wavelength, different chemical components) (Spehn,et al., 2000, Naeem, et al. 1994) 2) A highly diverse mixture results in greater space filling above and below ground and diversity can compensate for the failure of a single species due to bad germination, growth or survival (Spehn et al. 2000). 3) Nutrient leaching losses from ecosystems should decrease because of greater nutrient capture and/ or immobilization in more diverse ecosystems (Freitas, 1999). 4) In more diverse communities, there is a greater probability of the community containing productive and/or drought tolerant species (Tilman and Downing, 1994, Aarssen, 1997).

1.3 Previous study of the effect of different vegetation types on water runoff in ecosystem function and the aim of this study

This experiment repeated a previous study of the role of diversity in the maintenance of community and ecosystem function, same as Water runoff study in Chapter 4. In the previous study, the effect of different vegetation types with contrasting architecture on runoff quality and quantity was investigated in the experimental garden of the University of Sheffield. The experiment was conducted using 12 species. The combinations increased in their diversity: from simple monocultures through to increasingly complex mixtures. The vegetation types were three monocultures (*Festuca ovina*, *Carex flacca* and *Leontodon hispidus*) and five mixtures (composed of four grasses, four sedges, four fobs, the monoculture species and all twelve species respectively). The twelve species were *Festuca ovina*, *Helictotrichon pratense*, *Koeleria macrantha*, *Briza media*, *Carex flacca*, *Carex panicea*, *Carex pulicaris*, *Leontodon hispidus*, *Succisa pratensis*, *Viola riviniana*, *Campanula rotundifolia*, and a Bryophyte (Booth and Grime, 2001 and Dunnet et al, 2005). In this experiment, the same combinations, but different taxonomic groups and species were used. This experiment aimed to study the drought tolerance and irrigation requirements of different plant species as well as diversities.

2. Materials and methods

The experiment was carried out to study the drought tolerance of plant species in the different diversities of 12 species. These species were chosen from the three major taxonomic groups for extensive green roofs: forbs, sedums and grasses. Four species that are used in extensive green roofs were chosen from each of these taxonomic groups. The combinations increased in their diversity: from simple monocultures through to increasingly complex mixtures. The combinations were; 12 monocultures (*Armeria maritima, Origanum vulgare, Prunella vulgaris, Silene uniflora, Sedum acre* 'Minor', *S. album* 'Coral carpet', *S. rupestre, S. spurium* 'Coccineum', *Anthoxanthum odoratum, Festuca ovina, Koeleria macrantha, Trisetum flavescens*) and 5 mixtures (composed of four forbs, four sedums, four grasses and all 12 species mixture). The characteristics of 12 species are summarized in Table 4.1.1.

Table 4.1.1. The characteristics of the 12 experimental species (Brickwell, 2003, Evans, 1983, Hubbard, 1984, Snodgrass and Snodgrass, 2006, Stephenson, 1994)

Plant name	Plant type	Synopsis
A. maritima	Forb	*A. maritima* is widespread around the coast and in suitable inland localities. The species ranges from mild, moist Atlantic climates to extreme alpine environments at its altitudinal limits. It withstands exposure to most severe winds, and can tolerate extreme drought in areas of exposed stabilized single. Its poor shade tolerance excludes it from tall grassland. *A. maritima* grows on immature soils over a wide range of rock types often with high concentrations of sodium, calcium, magnesium or various heavy metals.
O. vulgare	Forb	*O. vulgare* is aromatic herb of relatively dry and infertile, usually calcareous soils. The species grows most vigorously at high external concentration of Ca and at low levels of supply exhibits Ca deficiency. This species exhibits only a limited capacity for lateral spread and is unable to coexist with taller, fast-growing species. *O. vulgare* has relatively deep root system and which often bears very long and numerous root hairs and allows the species to exploit subsoil water during periods of drought.
P. vulgaris	Forb	*P. vulgaris* is a winter-green, patch forming herb of grassland, typically associated with moist, moderately fertile soils. *P. vulgaris* is easily dominated by taller herbs and is abundant only in short turf, particularly in lawns and permanent pasture, where large clones may develop by vegetative expansion. The species exhibits some shade-tolerance and frequently occurs along woodland rides.
S. uniflora	Forb	*S. uniflora* is a clump forming plant that grows on coastal cliffs, shingle and gravelly soils. In spring, young shoots form a compact cushion-like plant of sea-green leaves. The white flowers with their inflated, bladder-like calyces grow on short stalks and cover the plant from May to July.
S. acre 'Minor'	Sedum	*S. acre* is leaf succulents forming tight cushions which expand vegetatively over shallow infertile soil and bare rock. *S. acre* is the one of the most widespread British succulents. The species is particularly characteristic of dry sand dunes and steeply sloping, S-facing exposure of rock. In addition to patch formation by creeping stems, vegetative spread may occur from detached shoots, or even leaves, which under suitably moist conditions root to form new colonies.
S. album 'Coral carpet'	Sedum	*S. album* is indigenous to every country in Europe except Ireland and Iceland. Throughout its range it grows at very contrasting altitudes and in a great variety of soils. It has been widely introduced everywhere. As a ground cover, the common forms spread rapidly, smother less rampant plants, and regenerate from a single fallen leaf.
S. rupestre	Sedum	*S. rupestre* is native to Central and Western Europe and has been introduced elsewhere in a multiple of settings from costal sand dunes to about 2000m in the Pyrenees Mountains.
S. spurium 'Coccineum'	Sedum	*S. spurium* originates from subalpine meadows in the Caucasus Range to Armenia and northern Iran. In most regions, on rocks in the middle and upper

		alpine zones. S. spurium is a very vulgar spreader.
A. odoratum	Grass	*A. odoratum* occurs as scattered individuals in a wide range of grasslands and to a lesser extent, open habitats particularly on slightly acidic soils. This species is earliest flowering in common pasture grass and has distinct spring and autumn peaks of vegetative growth. *A. odoratum* reaches maximum abundance in damp pastures and meadows of low to moderate fertility because sensitive to shading in tall derelict grassland.
F. ovina	Grass	*F. ovina* is one of the most consistent component species of infertile pasture in Britain. Fail competitive with faster-growing and broader-leaved turf grasses. Despite the relatively shallow root system, many of habitats it exploits are subject to severe drought. Feature of *F. ovina* which appear to contribute to its successes in dry habitats include xerophylly and an early shoot phenology and seed-set.
K. macrantha	Grass	*K. macrantha* is usually a short, winter green grass most characteristic of infertile calcareous grassland and rock outcrops. This species exhibits an intermediate degree of specialization compared with the various dominants with which it is able to coexist Its population may be expected under the conditions of climate, soil fertility and management to a greater degree of homeostasis than those of potential dominants.
T. flavescens	Grass	*T. flavescens* is a tufted grass of dry grassland and, to a lesser extent, rocky habitats, particularly on base-rich soils. In unmanaged grassland the species usually restricted to sites where the growth of more-productive species is checked by. This species is never more than a minor component of grassland communities, irrespective of management of turf height but capable of persisting through fluctuations of environment or management which are sufficient to bring about drastic change in the absence of the more specialized potential dominants.

This experiment was carried out in a green house of experimental garden, University of Sheffield. The seeds of forbs and grasses were obtained from Emorsgate Wild Seeds (Norfolk, UK) and were sown in 160 plug trays on 5th March 2006. After germination, the plants were thinned to one plant in each plug cell. Sedum spp. were obtained from The Alpine and Grass Nursery (Lincolnshire, UK). Leaf cuttings of the Sedums were taken on 5th March 2006 again in plug trays, with one cutting per plug cell. John Innes no.1 compost was used for the propagation. These plug trays were placed in the greenhouse with no temperature control and they were watered every other day. The plug plants were transplanted into flats (36.8 cm x 21.6 cm x 5.7 cm) in the middle of May 2006. The transplanting medium was a mixture of commercial green roof substrates which are based on crushed tile or brick and their organic matter was 10-15 % (Zinco sedum substrate and Zinco semi-intensive substrate 1:1). In each flat, 3000 g of substrate was used and 12 plants were planted. There were three replicates for each vegetation type. The vegetation types in flats were monoculture (one species only in each flat: 36 flats in total), forbs, sedums, grasses only (composing 4 species of each plant type in each flat: 9 flats in total), and the 12 species mixture (3 flats in total), resulting in a grand total of 48 flats were used in total. The flats were watered every other day until the experiment started. The plant flats were arranged in blocks by watering regimes and these flats were randomized within the block. On 1st September 2006, the watering treatment was started. There were three watering regimes, wet: once a week, moderate: once in two weeks, dry: once in three weeks. Enough water was applied for each flat until it started drain off the water.

Plant growth: height (longest shoots or leaves), shoot number, diameter (average of length and width) and relative appearance were measured every two weeks from 8th September 2006 to 19th November 2006 (in total 6 times). As Fig.4.1.2 shows, the growth of representative plants from each flat was measured to obtain three replicates of each species in total; one plant was measured in each monoculture, four plants (one plant from each species) for the 4 species mixture, and all plants for 12 species mixture. Their relative appearance was classified into five classes; 1 = severely stressed and completely dried out, 2= stressed, however, fresh leaves are little remained, 3= mild stressed and half of leaves are fresh, 4=a little stressed, however, most leaves appear healthy, 5=Healthy plants and no stress at all. This scale was set up with the reference of Montenrusso et al. (2005), however, 0 =dead was not used in this experiment since there was the possibility that even though they looked completely dead, they might recover after watering. In the final measurement, the plant survival was investigated. The plants which were completely dried out and did not produce the new shoots any more after watering were regarded as dead.

In December 2006, all plants were harvested and the roots were washed carefully. The plants were dried out in the green house until January 2007. After 7 days in the dessiccator, the shoot dry weight and root dry weight were measured. To test for significant difference between the treatments and the interaction, two-way ANOVA (Minitab Release 14) was used. When there were significant differences, means were separated by a Tukey test at the probability level $P<0.05$. For shoot and dry weight, the number of replications for individual species was different between diversities; 36 replications (12 plants x 3 flats) for monoculture, 9 replications (3 plants x 3 flats) for 4 species mixture and 3 replications (1 plants x 3 flats) for 12 species mixture. Although Minitab can perform a valid ANOVA on data with unequal replications, multiple comparison tests may not be entirely correct when there are unequal replicates (Warren et al., 2004). The contradiction was occurred in Tukey test, therefore, only ANOVA was used for the analysis of the shoot dry weight and root dry weight.

Fig.4.1.1 Overview of experiment

Armeria	*Armeria*	*Armeria*
Armeria	*Armeria*	*Armeria*
Armeria	*Armeria*	*Armeria*
Armeria	*Armeria*	*Armeria*

1. Monoculture

Armeria	*Origanum*	*Prunella*
Prunella	*Armeria*	*Origanum*
Silene	*Armeria*	*Silene*
Origanum	*Silene*	*Prunella*

2. 4 species mixture

S. acre	*Prunella*	*Trisetum*
Koeleria	*S. album*	*Armeria*
S. spurium	*Anthoxanthum*	*S. rupestre*
Silene	*Festuca*	*Origanum*

3. 12 species mixture

Fig.4.1.2 Example of plant arrangement

(Plants were randomly distributed in each replicate)

3. Results

3.1 Survival

The mean survival of plants in response to watering and diversity are shown in Fig. 4.1.3 (total) and Table 4.1.4 (individual species) respectively. Both results showed that after three weeks of no watering, the percentage of survival of plants decreased significantly. This result may suggest that the plants reached permanent wilting point between two to three weeks after no watering. 'Permanent wilting point' may be defined as the amount of water per unit weight or per unit soil bulk volume in the soil that is held so tightly by the soil matrix that roots cannot absorb this water and a plant will wilt (Kirkham,2004). Watering had a significant effect on the survival of all perennial and grass species. However, all Sedum spp. except *S. spurium* 'Coccineum', were not affected by the watering treatments. In the dry regime, only Sedum spp. and a low percentage of *A. maritima* were able to survive. *S. acre* 'Minor' and *S. rupestre* survived 100% regardless of any treatments.

For most of the species, survival increased as species richness increased in the both of moderate and dry regimes, although statistical analysis showed there was no significant effect in the diversity. Only two species, *O. vulgare* and *S. spurium* 'Coccineum' were affected by the diversity significantly. In the moderate regime, *O. vulgare* survived 100% in the 12 species mixture. However, the survival decreased to 88.89% and 8.33 % in the 4 species mixture and monoculture respectively. The same trend was observed in *P. vulgaris* in the moderate regime and *S. spurium* 'Coccineum' in the dry regime. *A. maritima, A. odoratum* and *F. ovina* in the moderate regime showed a lower percentage survival in the monoculture, whereas they showed 100% of survival in the both 4 species and 12 species mixture. These characteristics can be seen in the pictures in Table 4.1.3.

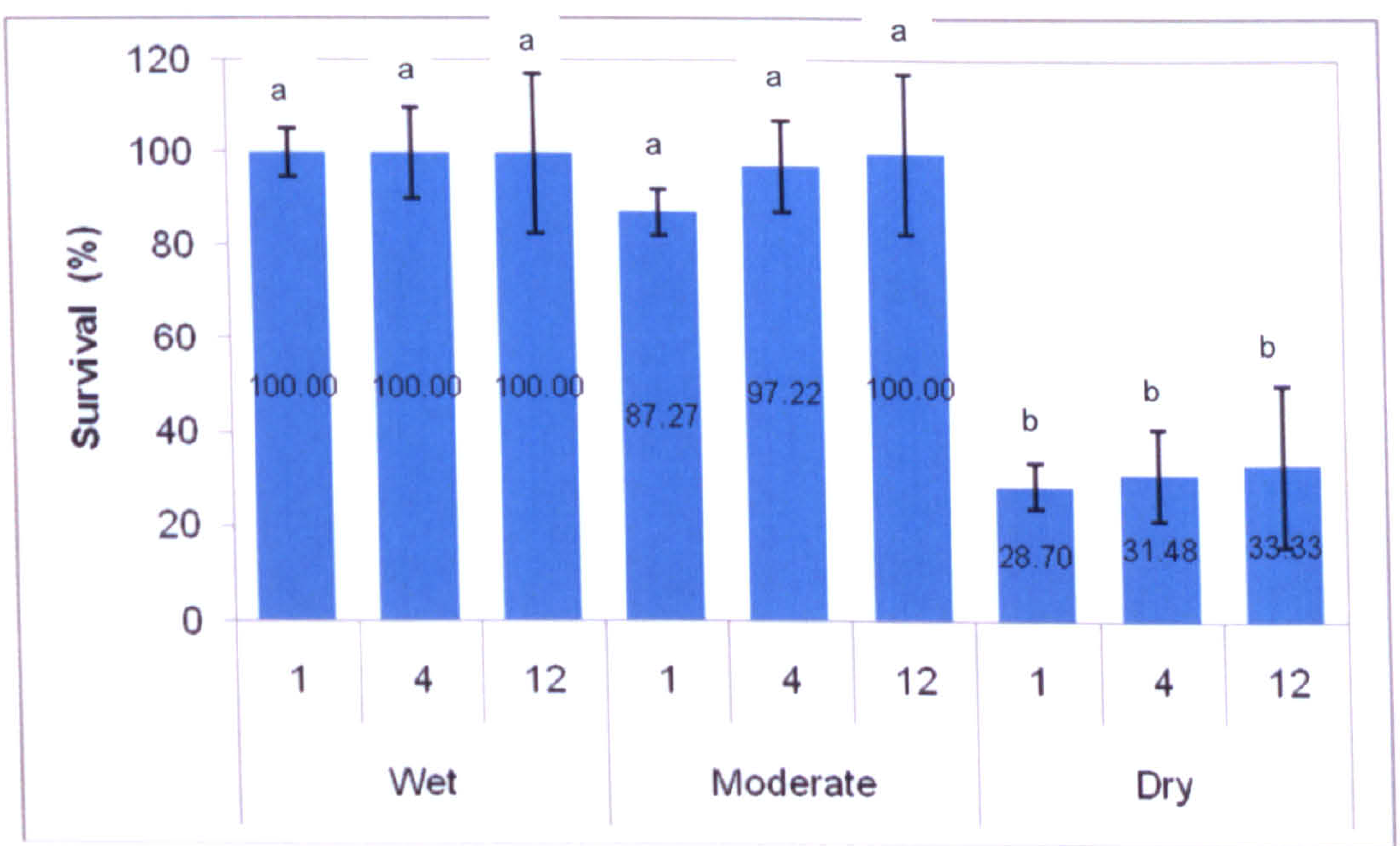


Fig.4.1.3 Total survival in response to the watering and the numebr of species (n=36) Error bars represent Standard Error. Means with the same letter do not differ significantly from each other.

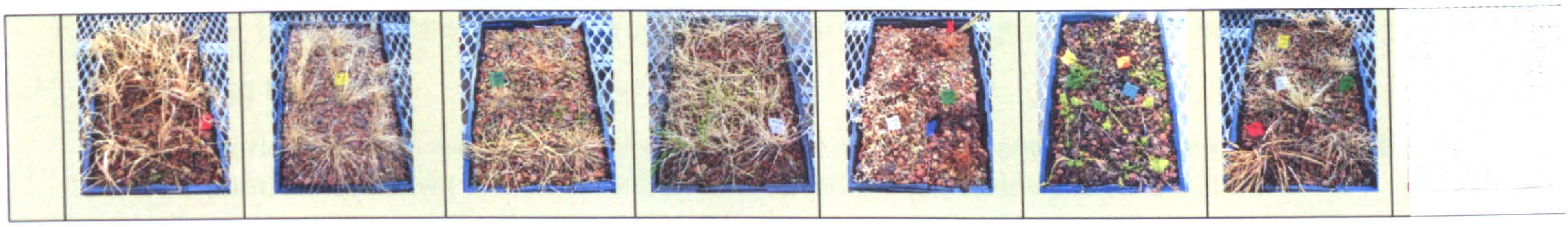
Table 4.1.4 Survival of individual plants in response to the watering and the diversity (n=3)

Watering	Wet			Moderate			Dry			SE	P
Number of species	1	4	12	1	4	12	1	4	12		
A. maritima	100 a	100 a	100 a	97.23 a	100 a	100 a	25.0 b	0 b	0 b	8.38	W<0.01
O. vulgare	100 a	100 a	100 a	8.33 b	88.89 a	100 a	0 b	0 b	0 b	4.63	W<0.01 D<0.01 W*D<0.01
P. vulgaris	100 a	100 a	100 a	66.67 a	88.89 a	100 a	0 b	0 b	0 b	11.71	W<0.01
S. uniflora	100 a	100 a	100 a	100 a	88.89	100 a	0 b	0 b	0 b	3.70	W<0.01

					a						
S. acre 'Minor'	100	100	100	100	100	100	100	100	100	-	-
S.. album 'Coral carpet'	100 a	100 a	100 a	100 a	100 a	100 a	100 a	88.89 a	100 a	3.70	ns
S. rupestre	100	100	100	100	100	100	100	100	100	-	-
S. spurium 'Coccineum'	100 a	100 a	100 a	100 a	100 a	100 a	19.44 b	88.89 a	100 a	4.44	W<0.01 D<0.01 W*D<0.01
A. odoratum	100 a	100 a	100 a	77.78 a	100 a	100 a	0 b	0 b	0 b	4.90	W<0.01
F. ovina	100 a	100 a	100 a	97.22 a	100 a	100 a	0 b	0 b	0 b	0.93	W<0.01
K. macrantha	100	100	100	100	100	100	0	0	0	-	-
T. flavescens	100	100	100	100	100	100	0	0	0	-	-

P=probability, W=watering regime, D=diversity, W*D=interaction between watering regime and anddiversity . Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

Table 4.1.5 Pictures of plant combinations under the different watering regime and number of plant species



W=Wet, M=Moderate, D=Dry (Note: The pictures were taken after experiment. There was the problem of mealy bug after experiment and *S. album* 'Coral carpet' monoculture *and S. spurium* 'Coccineum' do not look healthy)

3.2 Dry weight

3.2.1 Mean total dry weight per flat and the relationship between species richness and shoot biomass

To make clear differences in productivities in different vegetations, mean total dry shoot weight and dry root weight per flat in response to the watering and the diversity are shown in Table 4.1.6. A variety of biomass was observed among the different vegetations. There was a highly significant effect of vegetation types on both shoot and dry biomass in all watering regimes.

Mean root/shoot ratio per flat is shown in Table 4.1.7. Generally, the root/shoot ratio is shifted further in favor of the roots in the longer exposure to drought (Larcher, 2003). However, in this experiment, most of species showed the significantly better mean root/shoot ratio in the wet regime than in the dry regime

Relationships between number of species and mean total dry shoot weight and dry root weight per flat in all watering regime are shown in Fig.4.1.4 and Fig.4.1.5 respectively. No significant relationship was observed between species richness and the biomass. For shoot weight, the greater the number of species, the less total biomass in any watering regime (Wet: y=9.58 - 0.12x, R^2=0.7%, Moderate: y=8.72-0.06x, R^2=0.3%, Dry: y=7.13-0.11x R^2=0.8%). This result might suggest that competition between the plants was higher in the higher diversity of plants than monocultures and that diversity in vegetation reduces the vigour of potential dominant species. For dry root weight, the greater the number of species, the less total biomass in wet regime, whereas the more total biomass in moderate and dry regime (Wet: y=8.01-0.29x, R^2 =0.9%, Moderate: y= 5.02+0.09x, R^2 =0.3%, Dry: y= 1.76+0.09x, R^2 =1.5%). This may be because the species included have different root structures which probably they result in reduced interspecific competition below ground in drier conditions.

Table 4.1.6 Mean total dry shoot weight and dry root weight per flat in response to the watering (n=3)

SE= standard error, Letters of Tukey multiple comparison are compareing values within a colunm. Means with the same letter do not differ significantly from each other.

	Shoots			Roots		
	Wet	Moderate	Dry	Wet	Moderate	Dry
A. maritima monoculture	9.49 bcde	6.16 cd	4.54 ef	1.54 def	1.00 b	0.37 d
O. vulgare monoculture	5.86 def	5.96 cd	8.60 bcde	9.16 bc	4.30 b	7.91 a
P. vulgaris monoculture	16.83 a	15.15 a	12.62 ab	24.95 a	20.71 a	4.69 ab
S. uniflora monoculture	16.70 a	13.81 ab	10.13 bcd	4.79 cdef	4.85 b	0.69 cd
S. acre 'Minor' monoculture	7.79 cde	11.29 abc	15.13 a	0.76 f	1.00 b	0.89 cd
S. album 'Coral carpet' monoculture	1.47 f	3.39 d	4.52 ef	0.61 f	0.78 b	2.25 bcd
S. rupestre monoculture	12.45 abc	11.45 abc	4.99 ef	2.09 def	1.53 b	1.45 cd
S. spurium 'Coccineum' monoculture	7.10 de	8.38 abcd	6.13 cdef	1.11 ef	0.91 b	0.61 cd
A. odoratum monoculture	13.29 ab	10.10 abcd	10.62 abc	29.50 a	6.62 ab	3.96 bc
F. ovina monoculture	12.95 ab	9.44 abcd	4.63 ef	12.13 b	8.20 ab	0.53 cd
K. macrantha monoculture	8.65 bcde	6.47 bcd	2.66 f	5.75 cdef	5.61 b	0.43 d
T. flavescens monoculture	5.05 def	4.86 cd	3.77 ef	5.36 cdef	5.42 b	1.09 cd
Forb mixture	9.98 bcd	8.93 abcd	5.67 def	5.83 cdef	5.07 b	0.58 cd
Sedum mixture	4.87 ef	4.34 cd	4.43 ef	0.85 ef	0.68 b	0.69 cd
Grass mixture	6.70 de	8.68 abcd	4.24 ef	7.05 bcd	10.89 ab	1.47 bcd
12 mixture	9.67 bcde	8.96 abcd	7.31cdef	6.46 cde	5.98 b	3.84 bcd
SE mean	0.97	1.41	0.93	1.08	2.44	0.67
Probability	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01

Table 4.1.7 Mean root/shoot ratio per flat in response to the watering (n=3)

	Wet	Moderate	Dry	Probability
A. maritima monoculture	0.15 a ±0.03	0.16 a ±0.03	0.08 a ±0.03	ns
O. vulgare monoculture	1.54 a ± 0.11	0.73 b ± 0.11	0.92 b ± 0.11	P<0.01
P. vulgaris monoculture	1.49 a ±0.27	1.26 a ±0.27	0.39 a ±0.27	ns
S. uniflora monoculture	0.29 a ±0.03	0.37 a ±0.03	0.07 b ±0.03	P<0.01
S. acre 'Minor' monoculture	0.09 a ±0.01	0.09 a ±0.01	0.06 a ±0.01	ns
S. album 'Coral carpet' monoculture	0.51a ±0.06	0.23 b ±0.06	0.49 ab ±0.06	P<0.05
S. rupestre monoculture	0.17 a ±0.04	0.15 a ±0.04	0.29 a ±0.04	ns
S. spurium 'Coccineum' monoculture	0.17 a ±0.03	0.11 a ±0.03	0.10 a ±0.03	ns
A. odoratum monoculture	2.23 a ±0.22	0.71 b ±0.22	0.38 b ±0.22	P<0.01
F. ovina monoculture	0.94 a ±0.05	0.87 a ±0.05	0.11 b ±0.05	P<0.01
K. macrantha monoculture	0.66 a ±0.07	0.86 a ±0.07	0.17 b ±0.07	P<0.01
T. flavescens monoculture	1.08 a ±0.13	1.15 a ±0.13	0.32 b ±0.13	P<0.01

Forb mixture	0.59 a ±0.10	0.56 a ±0.10	0.10 b ±0.10	P<0.05
Sedum mixture	0.17 a ±0.02	0.15 a ±0.02	0.16 a ±0.02	ns
Grass mixture	1.07 a ±0.16	1.27 a ±0.16	0.34 b ±0.16	P<0.05
12 mixture	0.66 a ±0.09	0.66 a ±0.09	0.49 a ±0.09	ns

Values are mean ± Standard Error. Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

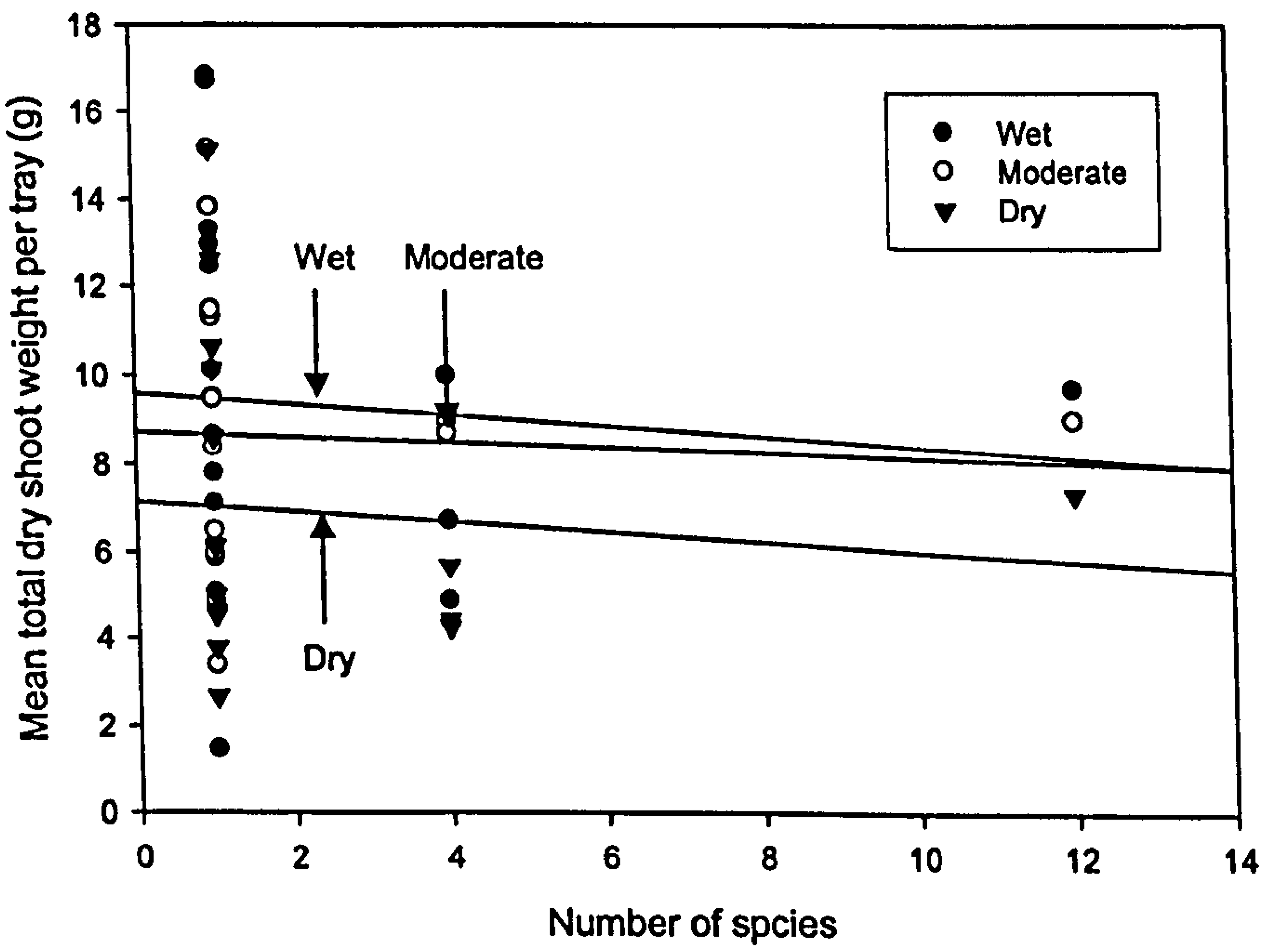


Fig.4.1.4 The relationship between number of species and mean total dry root weight per flat

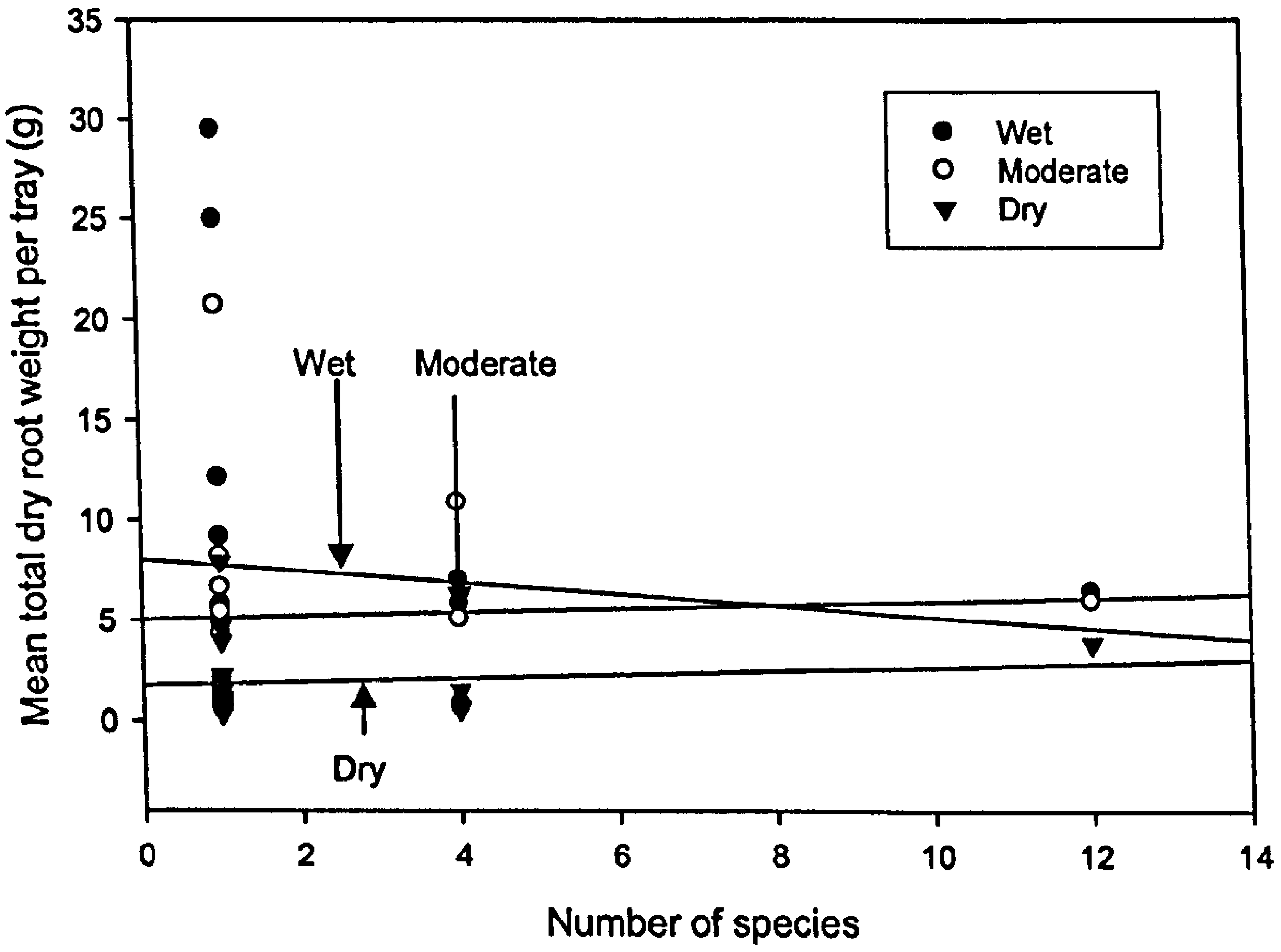


Fig.4.1.5 The relationship between number of species and mean total dry root weight per flat

3.2.2 Dry weight of individual species

The effect of watering and diversity on dry shoot weight and dry root weight of the individual species are shown in Table 4.1.8 and Table 4.1.9 respectively. It was predicted that watering would have a significant effect on growth of most species. However, 7 species (*O. vulgare, P. vulgaris,* all Sedum species, *A. odoratum*) for shoot weight and 5 species (*A. maritima, O. vulgare, Sedum* spp. except *S. album* 'Coral carpet') for root weight were not significantly affected by watering. Overall, the plants used showed better growth with more frequent watering. Exceptions were *S. acre* 'Minor' and *S. album* 'Coral carpet', they showed better growth in the drier conditions. This result may suggest that some Sedum spp. could survive well in dry conditions, however, they do not have the advantage that they can grow better even with additional watering.

For both dry shoot weight and dry root weight, most of the species were affected by plant diversity. However, a variety of responses were observed among the plants tested. For shoot biomass, seven species showed the greatest biomass in the monoculture and a similar pattern was observed for any watering regime. In contrast, for root biomass, many species showed their best growth in the monoculture when they have enough water, although more species showed best growth in the 12 species mixture in the dry regime. Interestingly, the best figures for shoot and root biomass tended to be in either monoculture or the 12 species mixture, but not in the 4 species mixture. Some species showed the same response to species richness regardless of the watering regime; the shoot growth of *O. vulgare*, *P. vulgaris*, *S. acre* 'Minor', *K. macrantha* were always greater in the monoculture, whereas *A. odoratum* showed the greatest biomass in the 12 species mixture. However, for most of the species, greatest biomass in different mixture was not achieved under same watering regimes. For example, the root biomass of *F. ovina* was the best in the monoculture in the wet regime, however, the 4 species mixture was the best in the moderate, the 12 mixture in the dry regime.

Table 4.1.8. Mean dry shoot weight of individual species in response to the watering treatments and the diversities (monoculture n=36, 4 species mixture n=12, 12 species mixture n=3)

Watering	Wet			Moderate			Dry			P
Number of species	1	4	12	1	4	12	1	4	12	
A. maritima	0.79 ± 0.04	0.44 ±0.08	0.61 ±0.13	0.51 ± 0.03	0.41 ± 0.08	0.51 ±0.13	0.38 ±0.04	0.27 ±0.08	0.39 ±0.13	W<0.01 D<0.01
O. vulgare	0.49 ±0.06	0.08 ± 0.11	0.17 ±0.20	0.50 ±0.06	0.15 ±0.11	0.13 ±0.20	0.72 ±0.06	0.10 ±0.11	0.18 ±0.20	D<0.01
P. vulgaris	1.40 ± 0.08	0.98 ± 0.17	0.79 ±0.29	1.26 ±0.08	1.19 ±0.17	1.24 ±0.29	1.05 ±0.08	0.86 ±0.17	0.98 ±0.29	ns
S. uniflora	1.39 ±0.09	1.83 ±0.19	2.10 ±0.33	1.15 ±0.09	1.22 ±0.19	1.46 ±0.33	0.84 ±0.09	0.66 ±0.19	0.75 ±0.33	D<0.01
S. acre 'Minor'	0.65 ±0.06	0.50 ±0.13	0.52 ±0.22	0.94 ±0.06	0.35 ±0.13	0.72 ±0.22	1.26 ±0.06	0.45 ±0.13	0.50 ±0.22	D<0.01 W*D<0.05
S. album 'Coral carpet'	0.12 ±0.02	0.20 ±0.05	0.14 ±0.08	0.28 ±0.02	0.09 ±0.05	0.19 ±0.08	0.38 ±0.02	0.18 ±0.05	0.16 ±0.08	D<0.01 W*D<0.05
S. rupestre	1.04 ±0.07	0.26 ±0.13	0.42 ±0.23	0.95 ±0.07	0.27 ±0.13	0.40 ±0.23	0.41 ±0.07	0.29 ±0.13	0.74 ±0.23	D<0.01 W*D<0.01
S. spurium 'Coccineum'	0.59 ± 0.05	0.66 ±0.10	0.57 ±0.17	0.70 ± 0.05	0.73 ± 0.10	0.73 ± 0.17	0.51 ± 0.05	0.55 ±0.10	0.85 ±0.17	ns
A. odoratum	1.11 ±0.07	0.81 ±0.15	1.69 ± 0.26	0.84 ±0.07	0.95 ±0.15	1.53 ±0.26	0.89 ±0.07	0.70 ± 0.15	1.67 ± 0.26	D<0.01
F. ovina	1.08 ±0.05	0.57 ± 0.09	0.57 ±0.16	0.79 ± 0.05	0.81 ±0.09	1.02 ±0.16	0.39 ± 0.05	0.33 ±0.09	0.29 ± 0.16	W<0.01 D<0.01 W*D<0.01
K. macrantha	0.72 ± 0.05	0.19 ±0.09	0.17 ± 0.16	0.54 ±0.05	0.08 ±0.09	0.04 ±0.16	0.22 ± 0.05	0.03 ±0.09	0.14 ±0.16	W<0.05 D<0.01 W*D<0.05
T. flavescens	0.42 ± 0.05	0.67 ±0.11	1.90 ± 0.19	0.40 ±0.05	1.05 ± 0.11	0.99 ± 0.19	0.31 ± 0.05	0.35 ±0.11	0.66 ± 0.19	W<0.01 D<0.01 W*D<0.01

Values are mean ± Standard Error. Statistical analysis is compareing values within a row. P=probability, W=watering regime, D=diversitiy, W*D=interaction between watering regime and diveristy. Means with the same letter do not differ significantly from each other.

Table 4.1.9. Mean dry root weight of individual species in response to the watering treatments and the diverstiy (monoculture n=36, 4 species mixture n=12,12 species mixture n=3)

Watering	Wet			Moderate			Dry			P
Number of species	1	4	12	1	4	12	1	4	12	
A. maritima	0.13 ±0.01	0.10 ±0.03	0.09 ±0.05	0.08 ±0.01	0.12 ±0.03	0.10 ±0.05	0.03 ±0.01	0.04 ±0.03	0.09 ±0.05	ns
O. vulgare	0.76 ±0.07	0.20 ±0.13	0.29 ±0.23	0.36 ±0.07	0.29 ±0.13	0.20 ±0.23	0.66 ±0.07	0.06 ±0.13	0.34 ±0.23	D<0.01
P. vulgaris	2.08 ±0.14	1.18 ±0.28	1.08 ±0.49	1.73 ±0.14	0.92 ±0.28	0.87 ±0.49	0.39 ±0.14	0.07 ±0.28	0.48 ±0.49	W<0.01 D<0.01
S. uniflora	0.40 ±0.03	0.47 ±0.07	0.52 ±0.12	0.40 ±0.03	0.37 ±0.07	0.71 ±0.12	0.06 ±0.03	0.02 ±0.07	0.42 ±0.12	W<0.01 D<0.01
S. acre 'Minor'	0.06 ±0.007	0.05 ±0.01	0.14 ±0.03	0.08 ±0.007	0.04 ±0.01	0.18 ±0.03	0.07 ±0.007	0.03 ±0.01	0.08 ±0.03	W<0.05 D<0.01 W*D<0.05
S. album 'Coral carpet'	0.05 ±0.01	0.03 ±0.03	0.09 ±0.05	0.06 ±0.01	0.02 ±0.03	0.11 ±0.05	0.19 ±0.01	0.05 ±0.03	0.05 ±0.05	D<0.01 W*D<0.01
S. rupestre	0.17 ±0.01	0.08 ±0.03	0.23 ±0.05	0.13 ±0.01	0.07 ±0.03	0.18 ±0.05	0.12 ±0.01	0.06 ±0.03	0.27 ±0.05	D<0.01
S. spurium 'Coccineum'	0.09 ±0.01	0.12 ± 0.02	0.27 ±0.04	0.08 ±0.01	0.10 ± 0.02	0.25 ± 0.04	0.05 ±0.01	0.09 ±0.02	0.25 ±0.04	D<0.01
A. odoratum	2.46 ± 0.12	0.65 ± 0.24	1.02 ± 0.41	0.55 ±0.12	0.95 ±0.24	1.05 ±0.41	0.33 ± 0.12	0.15 ±0.24	0.81 ±0.41	W<0.01 D<0.01 W*D<0.01
F. ovina	1.01 ±0.05	0.54 ±0.11	0.38 ±0.18	0.68 ±0.05	1.02 ± 0.11	1.01 ±0.18	0.04 ±0.05	0.15 ±0.11	0.30 ±0.18	W<0.01 W*D<0.01
K. macrantha	0.48 ± 0.04	0.28 ± 0.08	0.22 ±0.13	0.47 ± 0.04	0.20 ±0.08	0.19 ±0.13	0.04 ± 0.04	0.02 ±0.08	0.06 ±0.13	W<0.01 D<0.01
T. flavescens	0.45 ±0.07	0.88 ± 0.14	2.13 ± 0.24	0.45 ± 0.07	1.46 ±0.14	1.11 ±0.24	0.09 ±0.07	0.18 ±0.14	0.69 ±0.24	W<0.01 D<0.01 W*D<0.01

Values are mean ± Standard Error. Statistical analysis is compareing values within a row. P=probability, W=watering regime, D=diversity, W*D=interaction between watering regime and diversity. Means with the same letter do not differ significantly from each other.

3.3 Final growth of individual plants

The final growth of individual plants (height, shoot number, diameter) is shown in Table 4.1.10. Only the living parts were measured for growth, therefore, all forbs and grasses except *A. maritima* showed 0 in the dry regime. Overall, there was a trend that plant growth was the best in the wet regime. The growth of all forbs and grasses was significantly affected by the watering, whereas *Sedum* spp., except *S. spurium* 'Coccineum', were not affected by the watering. The survival of *Sedum* spp. in the dry regime was high and their growth in the dry regime was as good as those in the wet regime.

A variety of responses for the diversities was observed among the plants tested. *O. vulgare, S. album* 'Coral carpet' and *K. macrantha* showed the best growth in the monoculture, whereas *S. uniflora, A. odoratum, T. flavescens* showed the best growth in 12 mixture.

Table 4.1.10 Mean final growth (height, shoot number and diameter) of individual species in response to the watering and the diversity (n=3)

Watering		Wet			Moderate			Dry			SE	P
Number of species		1	4	12	1	4	12	1	4	12		
A.maritima	Shoot length (cm)	8.50 a	5.77 ab	7.40 ab	6.33 ab	6.33 ab	6.63 ab	2.07 bc	0 c	0 c	0.99	W<0.01
	Shoot number	6.67 a	3.33 abc	5.00 abc	5.00 abc	6.00 abc	2.00 abc	0.67 bc	0 c	0 c	1.12	W<0.01
	Diameter (cm)	11.08 a	8.18 ab	10.28 a	9.97 a	9.13 a	8.17 ab	3.05 bc	0 c	0 c	1.19	W<0.01
O. vulgare	Height (cm)	19.10 a	7.33 ab	15.00 ab	0 b	11.07 ab	9.40 ab	0 b	0 b	0 b	3.56	W<0.01
	Shoot number	47.00 a	10.00 b	9.00 b	0 b	8.67 b	7.67 b	0 b	0 b	0 b	4.03	W<0.01 D<0.05 W*D<0.01
	Diameter (cm)	9.75 a	4.45 bc	8.07 abc	0 c	5.50 abc	3.28 abc	0 c	0 c	0 c	1.04	D<0.01 W*D<0.01
P. vulgaris	Shoot length (cm)	6.20 a	5.00 a	5.47 a	4.30 a	4.90 a	7.07 a	0 b	0 b	0 b	0.87	W<0.01
	Shoot number	13.33 a	12.67 ab	12.67 ab	10.67 ab	10.33 ab	15.33 a	0 b	0 b	0 b	2.56	W<0.01
	Diameter (cm)	12.73 a	9.02 a	9.05 a	8.38 ab	9.57 a	14.12 a	0 b	0 b	0 b	1.70	W<0.01
S. uniflora	Shoot length (cm)	15.13 ab	26.10 a	29.13 a	10.07 ab	14.10 ab	22.90 a	0 b	0 b	0 b	3.72	W<0.01 D<0.05
	Shoot number	42.00 a	38.00 ab	37.67 ab	14.67 bc	13.00 bc	27.00 b	0 c	0 c	0 c	5.07	W<0.01
	Diameter (cm)	17.13 a	18.88 a	22.05 a	11.18 ab	10.43 ab	19.63 a	0 b	0 b	0 b	2.47	W<0.01
S. acre 'Minor'	Shoot length (cm)	4.30 a	4.47 a	4.80 a	4.30 a	4.07 a	4.47 a	4.27 a	3.43 a	4.33 a	0.43	ns
	Shoot number	133.33 ab	108.00 ab	91.33 ab	142.00 a	70.00 b	132.67 ab	129.67 ab	114.33 ab	109.33 ab	13.76	D<0.05
	Diameter (cm)	8.33 a	7.03 a	6.88 a	6.92 a	6.58 a	7.72 a	8.18 a	8.15 a	7.37 a	0.47	ns
S. album 'Coral carpet'	Shoot length (cm)	10.17 ab	7.87 b	8.50 b	10.23 b	7.37 b	6.50 b	12.07 a	7.10 b	8.17 b	0.78	D<0.01
	Shoot number	130.67 ab	74.67 ab	39.67 b	106.33 ab	109.67 ab	55.33 b	153.33 a	92.33 ab	84.67 ab	19.41	D<0.01
	Diameter (cm)	11.33 a	9.70 a	9.73 a	12.05 a	10.03 a	9.53 a	13.30 a	9.38 a	10.32 a	1.04	D<0.05
S. rupestre	Height (cm)	14.43 a	12.50 a	14.67 a	16.93 a	9.40 a	9.90 a	12.40 a	11.53 a	15.10 a	1.66	ns
	Shoot number	15.33 a	8.00 a	8.00 a	10.67 a	7.67 a	7.00 a	11.00 a	9.00 a	13.67 a	2.58	ns
	Diameter (cm)	13.27 a	8.33 a	10.10 a	14.98 a	6.17 a	9.55 a	9.78 a	8.80 a	15.02 a	1.97	D<0.05
S. spurium 'Coccineum'	Height (cm)	21.67 a	20.43 ab	12.17 b	19.97 ab	18.73 ab	19.43 ab	0 c	14.20 ab	18.43 ab	1.70	W<0.01 D<0.05 W*D<0.01
	Shoot number	15.33 ab	11.00 abc	9.00 bc	15.00 ab	22.67 a	16.33 ab	0 c	20.67 ab	15.67 abc	2.38	W<0.01 D<0.01 W*D<0.01
	Diameter (cm)	19.88 a	11.48 ab	10.08 b	14.93 ab	15.30 ab	16.28 ab	0 c	13.32 ab	12.50 ab	1.97	W<0.01 W*D<0.01
A. odoratum	Height (cm)	19.50 ab	16.17 ab	25.93 a	8.00 bc	16.87 a	18.70 a	0 c	0 c	0 c	2.41	W<0.01 D<0.05
	Shoot	10.33	11.33	10.33	6.00	9.00	17.00	0 c	0 c	0 c	1.84	W<0.01

	number	ab	ab	ab	bc	abc	a					W*D<0.05
	Diameter (cm)	20.83 a	22.50 a	28.22 a	10.22 a	15.37 a	22.77 a	0 b	0 b	0 b	2.79	W<0.01 D<0.05
F. ovina	Height (cm)	15.10 ab	11.43 bc	13.40 abc	17.20 a	9.40 c	12.23 abc	0 d	0 d	0 d	1.00	W<0.01 D<0.01 W*D<0.05
	Shoot number	33.33 a	31.00 a	28.00 a	21.00 a	32.00 a	34.67 a	0 b	0 b	0 b	4.12	W<0.01
	Diameter (cm)	16.77 a	13.60 a	16.83 a	12.00 a	12.05 a	16.17 a	0 b	0 b	0 b	1.10	W<0.01 D<0.05
K. macrantha	Height (cm)	12.50 a	9.30 ab	11.90 ab	8.50 ab	5.77 b	6.27 b	0 c	0 c	0 c	1.20	W<0.01
	Shoot number	24.33 ab	16.33 abc	9.00 bc	35.67 a	7.00 bc	4.00 bc	0 c	0 c	0 c	3.73	W<0.01 D<0.01 W*D<0.01
	Diameter (cm)	17.72 a	12.00 ab	11.83 ab	12.60 ab	7.35 bc	6.98 bc	0 c	0 c	0 c	1.51	W<0.01 D<0.01
T. flavescens	Height (cm)	17.80 ab	17.73 b	30.40 a	11.60 c	13.23 bc	15.37 bc	0 d	0 d	0 d	1.02	W<0.01 D<0.01 W*D<0.01
	Shoot number	14.00 ab	17.67 a	27.33 a	21.67 a	14.67 ab	19.33 a	0 b	0 b	0 b	3.03	W<0.01
	Diameter (cm)	15.98 b	21.43 b	24.33 a	16.03 b	15.20 b	19.43 ab	0 c	0 c	0 c	1.44	W<0.01 D<0.05

Statistical analysis is compareing values within a row. SE= Standard Error P=probability, W=watering regime, D=diversity, W*D=interaction between watering regime and diversity.Means with the same letter do not differ significantly from each other.

3.5 Appearance of moisture stress symptoms (Effect of watering)

Changes of appearance in moisture stress symptoms over time are shown in Figs.4.1.6 – Fig.4.1.8. Only results of the moderate and dry watering regime were shown because all plants in the wet regime showed '5=Healthy plants and no stress at all'. The plants, which were evaluated as less than '3= mild stressed and half of leaves are fresh' in 23 days after starting of the experiment, could not survive at all. This result suggests that watering of these plants is necessary before they reach the stage that half of leaves are dried out. In the forbs, the drought tolerance of four species was clear; *A. maritima* showed the best visual rating followed by *P. vulgaris*, *S. uniflora* and *O. vulgare*. In the Sedums, only *S. spurium* 'Coccineum' showed a stress symptom, however, compared to the other taxonomic group, this symptom appeared gradually. In the grasses, *K. macrantha* did not show any stress symptoms in the moderate regime. *T. flavescens* recovered from the drought well in the moderate regime and showed the '5=Healthy plants and no stress at all' in the final measurement.

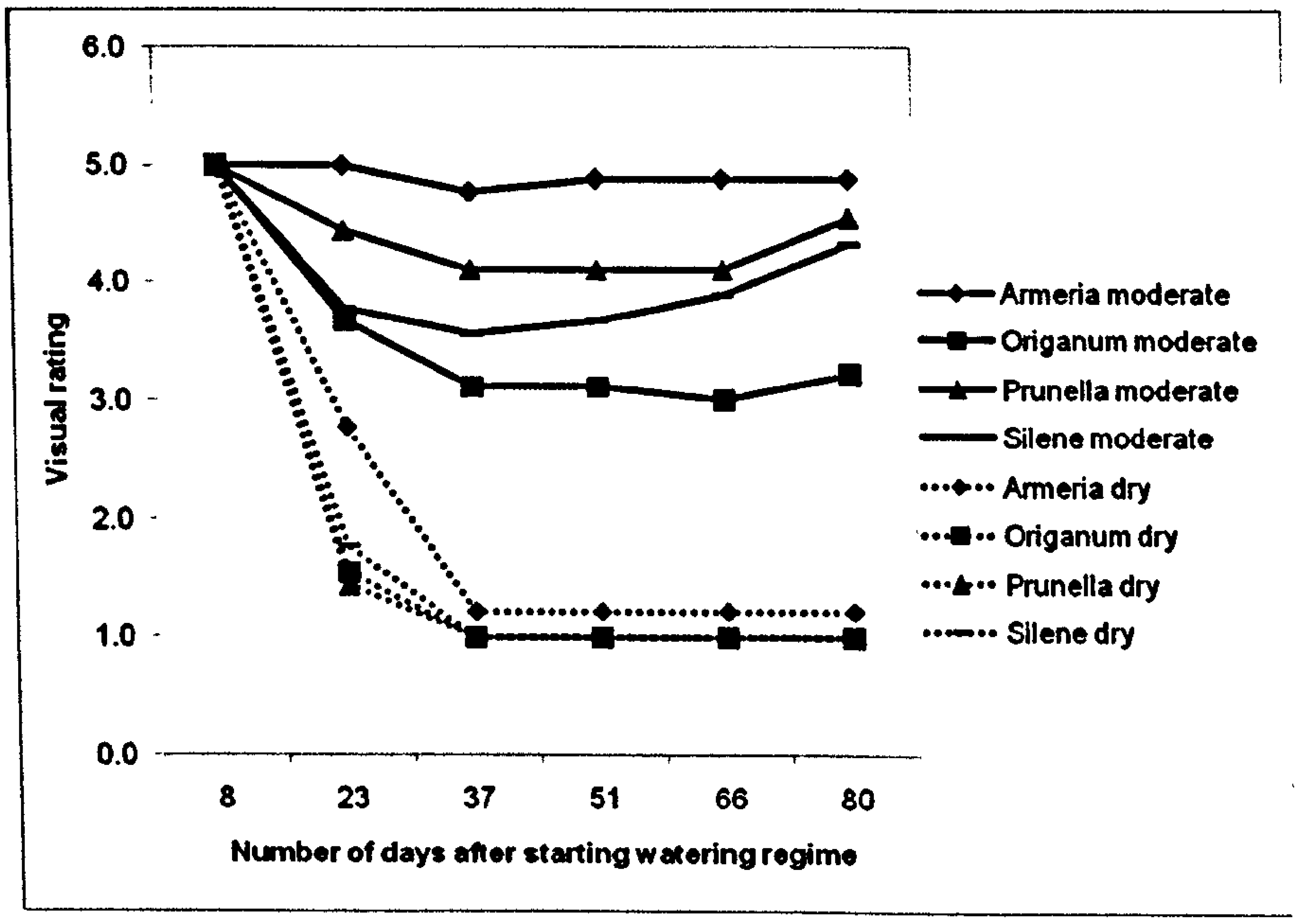


Fig.4.1.6 Change of visual rating of forbs over time

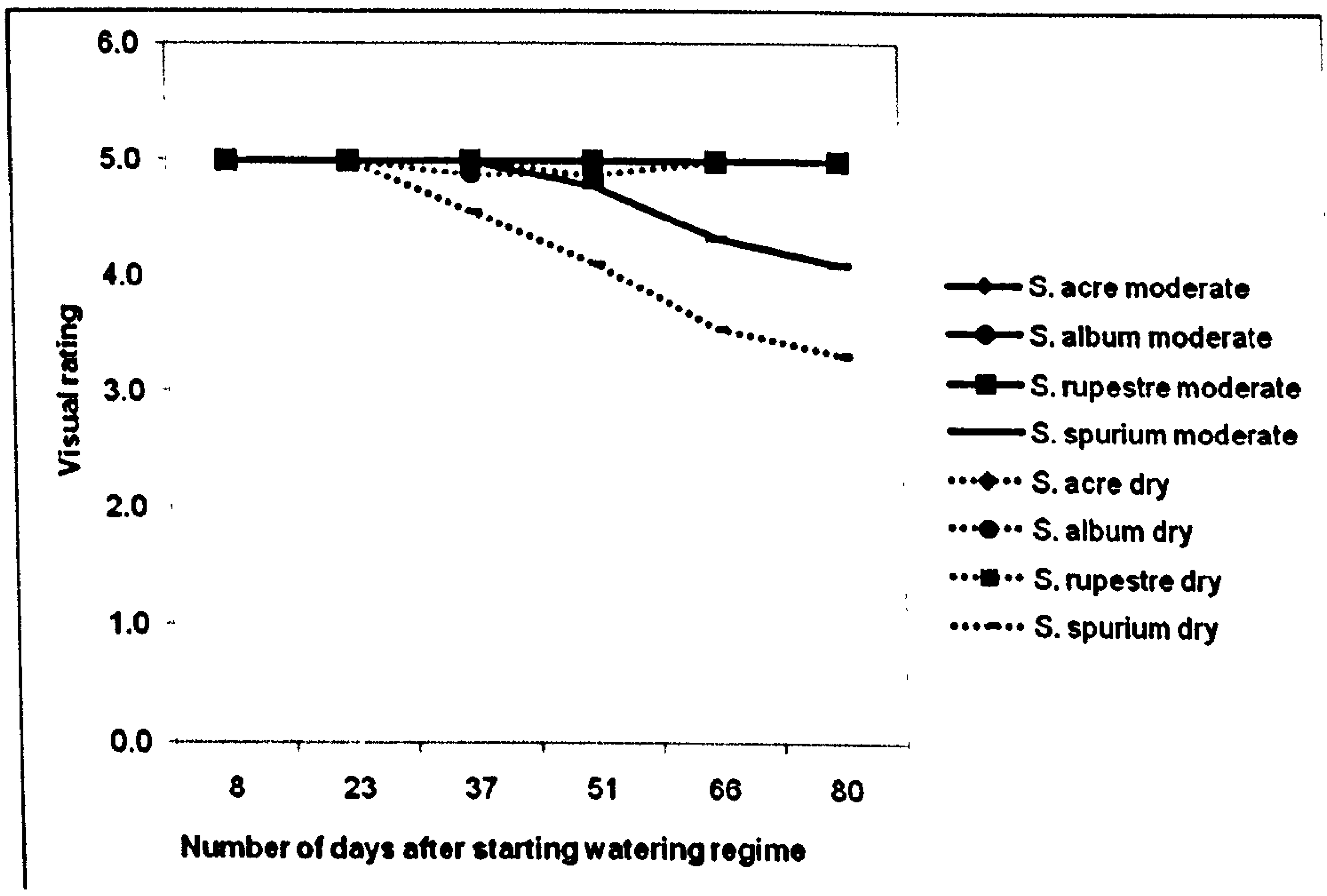


Fig.4.1.7 Change of visual rating of sedums over time

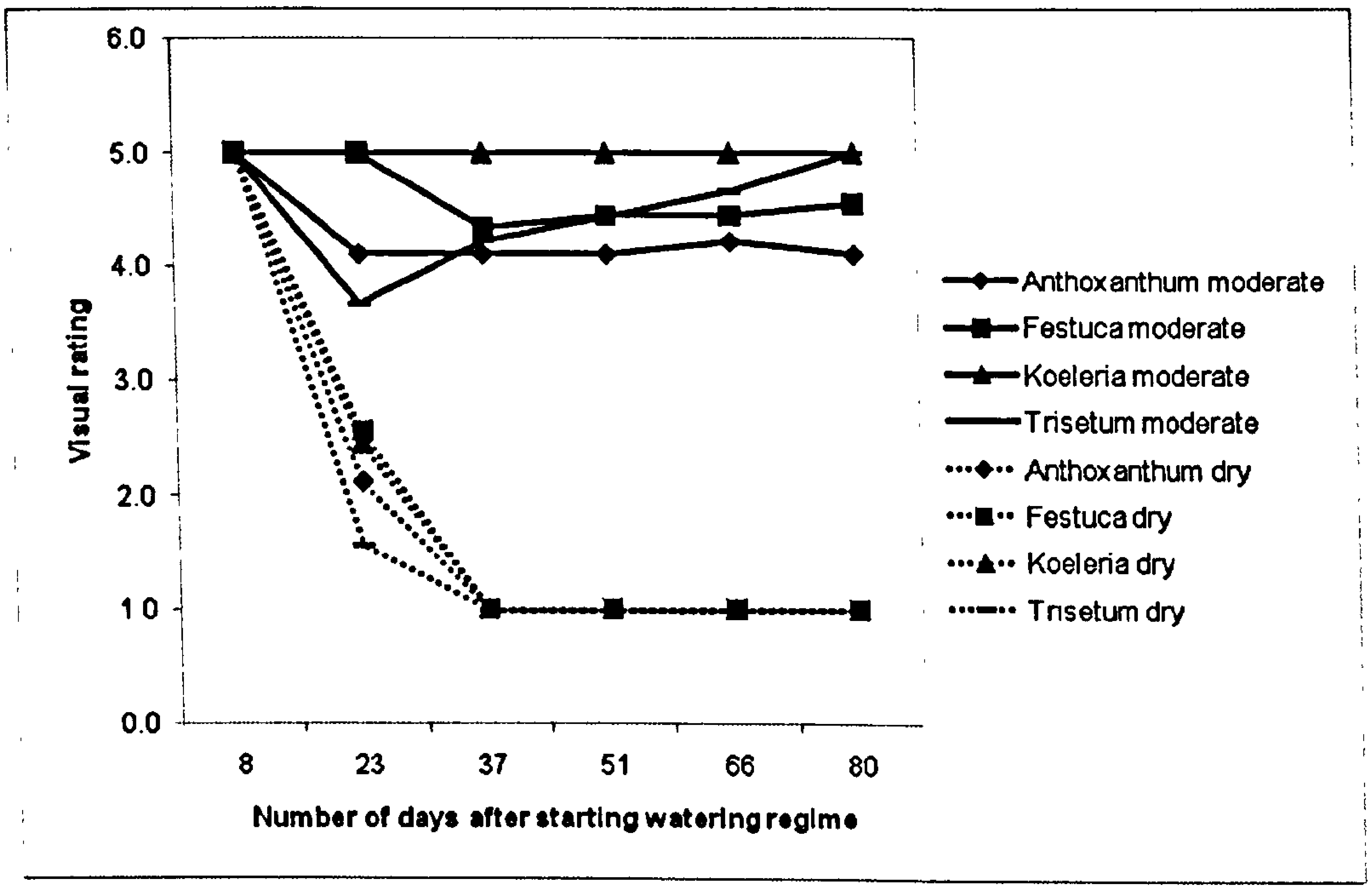


Fig.4.1.8 Change of visual rating of grasses over time

3.6 Summary of performance of individual species

The performance of individual species was summarized in Table 4.1.11. For successful plant selection for extensive green roofs, it is necessary to understand the characteristics of the plants involved. Overall, *Sedum* spp. were the most drought tolerant and except for *S. spurium* 'Coccineum' they were able to survive well even after three weeks of no watering. Between forbs and grasses, *A. maritima, K. macrantha* and *T. flavescens,* which are small plants, had greater drought tolerance and showed higher survival. The response in the diverse combinations was different for different species. *O. vulgare* and *S. spurium* 'Coccineum' showed significantly higher survival in more plant species diversity. The growth of *A. odoratum* and *T. flavescens* were encouraged as the number of species increased whereas *O. vulgare, P. vulgaris* and *K. macrantha* showed the opposite response. Overall, *P. vulgaris, S. uniflora* and *S. rupestre* showed vigorous shoot growth, whereas, the shoot biomass of *O. vulgare, S. album* 'Coral carpet' and *T. flavescens* was less. The root growth of *P. vulgaris* was much higher than one of the other species. *A. maritima* and all four sedum spp. had fine and fibrous roots and the root biomass was small.

Table 4.1.11 Summary of performance of individual species

	Drought tolerance	Response for more species richness	Overall shoot growth	Overall root growth
A. maritima	High between forbs			Low
O. vulgare		Higher survival but less growth	Low	
P. vulgaris		Less growth	High	High
S. uniflora			High	
S. acre 'Minor'	High			Low
S. album 'Coral carpet'	High		Low	Low

S. rupestre	High		High	Low
S. spurium 'Coccineum'	High but low between sedums	Higher survival		Low
A. odoratum		More shoot growth		
F. ovina				
K. macrantha	High between grasses	Less growth		
T. flavescens	High between grasses	More growth	Low	

4. Discussion

4.1 Effect of Watering

If green roofs are carefully designed, with an appropriate plant mix and substrate, and if the plants have been properly established, there should be no need for irrigation except in the most arid climate (Dunnett and Kingsbury, 2004a). However, it might be necessary to make use of the possibility of supplemental watering, especially where non-succulent plants are used, since the weather have been unpredictable recently. In this experiment, all forbs and grasses reached permanent wilting point between two to three weeks after watering, and it is required to water them once a week to maintain the visually attractive forms. However, water availability in a substrate may be different between different green roofs due to plant selection, microclimate, substrate types and their depths. Hence, it is impossible to generalize that supplemental watering is always necessary after two weeks of no watering to grow forbs and grasses on extensive green roofs. It might be reasonable to judge drought from the appearance of plants as well; in this study, the plants which had more than half of their leaves dead were not able to survive. As Handreck and Black (2002) pointed out, careful observation is necessary to give an appropriate irrigation regime; learning to recognize subtle changes in plant colors and appearances that are early warning of unacceptable stress.

As expected, it was shown that the drought tolerance of sedums was superior to that of forbs and grasses. However, the response to drought of sedums was different between species and this was similar to findings of some previous studies (Nagase and Thuring, 2006, Van Woert, et al., 2005). In this study, *S. spurium* 'Coccineum' was less drought tolerant and showed stress symptom gradually in a dry regime. In a previous study of the effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof taxa, *S. acre, S. album* 'Bella d'Inverno' and *S. rupestre* showed 100% survival in any regimes, however, *S. spurium* 'Summer Glory' survived 75 % in 2.5 cm of substrate and 87% in 7.5cm respectively (Durham et al., 2007). It was also observed that *S. spurium* showed severe drought symptoms in the dry summer in 2006 on a green roof in Rotherham UK. It seems that *S. spurium* might be less drought tolerant than some *Sedum* spp. Interestingly, *S. acre* 'Minor' and *S. album* 'Coral carpet' showed better growth in the drier regime. A negative response of *Sedum* spp. for additional watering was reported for *S. mexicanum* in a high temperature of a green house (Iijima, 2001) and *S. acre* on a roof (Dunnett, 2004a). They possibly caused a root rot in the wet regime. Stephenson (1994) also pointed out that generally Sedums are more likely to be harmed by overwatering than by less watering. *S. rupestre* showed the best growth in the wet regime, however, no plants died in the dry regime. This result suggests that *S. rupestre* may be able to tolerate both wet and dry conditions. This characteristic would be the best for extensive green roofs since water a fluctuation tends to be high in a thin substrate.

Between the forbs, *A. maritima* had the best drought tolerance, although both shoot and root biomass were small and their growth may be slow. According to Woodell and Dale (1993), *A. maritima* ranges from mild moist climates to extreme alpine environments at its altitudinal limits. It withstands exposure to most severe winds and can tolerate extreme drought because its tap root enables it to utilize water from lower levels of the soils. Deep tap root species may not be suitable for extensive green roofs, however, shallow tap root species such as *Armeria* can adapt to shallow substrates and might show more drought tolerance than the forbs with shallow spreading fibrous roots. Further experiments are required to prove this. *P. vulgaris* and *S. uniflora* showed drought symptoms in the moderate watering regime at the beginning, however, they recovered gradually. These two species had vigorous growth with sufficient watering. One of the reasons of the sensitivity to water stress was presumably due to greater physical size which increased the difficulty in maintaining water supplies to the most distal parts (Hitchmough, 1994b). They might achieve quick growth on roofs when they receive enough water and this characteristic should be considered in a planting design. *O. vulgare*, which is a semi-woody type of plant, showed the least drought tolerance between the forbs. The other species used had creeping habits whereas this species exhibits only a limited capacity of lateral spread. However, it was unclear that whether these different morphologies were related to the drought tolerance exhibited by the different species. Further research is necessary to evaluate the drought tolerance of different species with different forms.

Between the grass species, *A. odoratum* had a lower survival than the other three species. Although the natural habitats of all four species tend to be dry and infertile soils, *A. odoratum* reaches maximum abundance in damp pastures and meadows, where there is higher moisture availability. *F. ovina* would appear to succeed in dry habitats because of xerophyl morphology and physiology and an early shoot phenology and seed-set. Both *K. macrantha* and *T. flavescens* are associated with a range of soil types, moisture and fertility levels. Generally, *F. ovina* is more xeromorphic than *K. macrantha* (Grime et al., 1988). However, *K. macrantha* showed the better performance in the dry condition in this study. The reason was not clear but *K. macrantha* showed the slowest growth between the grasses and this might be related to its drought tolerance. *T. flavescens* was able to recover from the drought well, although *A. odoratum* and *F. ovina* kept the same visual rating (Fig.4.1.8). Kemp and Culvenor (1994) pointed out that the most important strategy for adaptation to dry conditions is not maintenance of production during drought, but the ability to survive and recover rapidly after getting water.

According to many previous studies, the tendency observed that the root/shoot ratio increased when they did not have enough watering to improve the water uptake (e.g. Struik and Bray,1970, Mortimer, 1992). Interestingly, in this experiment, most of species showed the least mean root/shoot ratio in the dry regime. One of the reasons might be that except *Sedum* spp., most plants died in dry regime and their roots were easy to break in the crushed brick substrate when they were harvested. Another possible explanation would be the plant strategy; the forbs and grasses used in this experiment might have strategy of resistance for drought (the ability of the plant biomasss to resist displacement from control levels). In the previous study of drought and nutrient stress in grassland using *Festuca ovina* and *Arrhenatherum elatius*, the high survival of *F. ovina* appears to be due to drought resistance rather than evasion since the depth of root penetration of *F. ovina* tended to be inferior to that of *A. elatius* (Grime and Curtis,1976). The root penetration is important for dry condition of green roofs, therefore, it is necessary to confirm this using loose substrate to study root structures.

4.2 Effect of diversity

The striking result of this study was that that overall survival increased as species richness increased in the dry condition. This was consistent with the previous research on biodiversity and ecosystem functioning (Mulder et al. 2001, Tilman and Downing, 1994). As mentioned in the introduction, there are many explanations for this, however, moisture absorption and retention maybe one of the important reasons. Rixen and Mulder (2005) explained that a more complex architecture of a high diversity vegetation slows down the rate at which water hitting top of a canopy reaches the soil and increases the amount of water absorbed. In the water runoff study using same species and diversity (*O. vulgare* was replaced by *Leontodon hispidus*) in this thesis (Chapter

4-1), the 12 species mixture showed the third highest water retention followed by the monoculture of *A. odoratum* and *T. flavescens*. It was estimated that these two grasses could retain more water because of their funnel structure with tall, large leaf surface and vigorous roots, however, probably the water usage of the plants was also high and their water usage would be uniform. On the contrary, the plants in the 12 species mixture were able to use the water more effectively, therefore, the plant survival was higher. This is because they include Sedum spp. which use little water and the different species may have a different peak of growth and reproduction, which would cause different water harvesting abilities (Solbrig,1994).

The results of this experiment have shown no evidence of beneficial effects of increasing species richness on productivity. Booth and Grime (2001) showed that when mean above-ground biomass is plotted against the species richness of each synthesized community in their experiments on the influence of plant diversity on runoff from vegetation, that there was a weak positive relationship after two years of experiment. However, this might be not because of species richness but the presence of certain species in the community. Grime (2001) explained that sedges would have prospered under the conditions of the experiment and their more frequent inclusion in the species-rich seed mixtures would have led inevitably to confounding of a beneficial 'sedge effect' with increasing species richness and rising productivity. Grassland sedges posses dauciform roots, specialized structures which are suspected to be capable of facilitating the mineralization and capture of phosphorous, the limiting element for plant growth in many calcareous ecosystems.

Root growth showed a more positive response to species richness compared to shoot biomass, especially in the dry condition. This is probably because the species used have different characteristics of root structures (shallow rooted sedums, dense rooted grasses). Yeaton et al. (1977) suggested that a vertical separation of root systems is the mechanism through which interspecific competition is reduced and co-existence maintained between these associated species of plants. Indeed, in an environment in which the availability of moisture is variable and limited, seasonal growth strategies are important in regard to co-existence of different species. For example, plants with superficial root systems require a strategy permitting rapid absorption and storage of water before it penetrates to lower levels, whereas those with deeper roots may be in the rain shadow of more surface - rooting species during periods of low penetration, and hence are likely to be drought-resistant and able to wait for penetration of water from the gentle rains of long duration.

Each species showed a different response to being in the more diverse mixtures and no particular diversity was observed to have a high biomass production. More than half the species showed better shoot biomass in the monoculture than in the mixture. According to Bach and Hruska (1981), various plant parameters are influenced by plant diversity. For example, leaf area is greater or lesser in monocultures than in mixtures depending on the densities and particular species studied. In this study, especially the shoot biomass of *O. vulgare* decreased significantly as the species richness increased. This is probably because of competition with the other species which are better able to obtain certain limited resources in the mixture. This result may suggest that diversity in vegetation reduces the vigour of potential dominant species. Where resources are abundant, plants can be equally competitive and the best competitor may eventually less competitive species. In general, greatest species diversity is promoted at moderate intensities of environmental stress/or disturbance (Dunnett, 2004b), and extensive green roofs, with relatively generous substrate depths would be appropriate for species rich vegetations. On the contrary, some species such as *A. odoratum* and *T. flavescens* showed the best growth in the 12 species mixture regardless of the watering regime. They can be good competitors by rapidly depleting a resource or by being able to continue growth at depleted resource levels (Goldberg, 1990). However, the timescale of this experiment was too short to decide these species have potential to be dominant in the plant communities.

Interestingly, overall growth of the 4 species mixture tends to be less than the 12 species mixture. According to Yeaton and Cody (1976), interspecific competition occurs between species with similar morphologies. In this study, the combination of 4 species belongs to the same functional group and they have similar structures. Hence, probably they have to compete with each other more in the 4 species mixture than those in the 12 species mixture and the 4 species mixture do not have much advantage for complementary use of resources as the 12 species mixture. Diaz et al. (2001) also indicated that functional differences have more influence on ecosystem processes than has species richness.

5. Conclusion

It was concluded that the forbs and grasses used in this study reached permanent wilting point after two to three weeks of no watering and they were not able to recover after half of their total leaves appeared to visually dry out. The forbs and grasses were required to be watered once a week to maintain their visually attractive forms. Overall, *Sedum* spp. were the most drought tolerant group and, except for *S. spurium* 'Coccineum', they were able to survive well and maintain their good visual quality even with three weeks of no watering. For the forbs and grasses, *A. maritima*, *K. macrantha* and *T. flavescens*, which have a small size, had drought tolerance and showed higher survival. Overall survival increased as species richness increased, although the results of this experiment have shown no evidence of beneficial effects of increasing species richness on productivity. Some species which had the best growth in the monoculture reduced their growth in the mixture. This result may suggest that diversity in vegetation, under conditions of environmental stress, reduces the vigour of potential dominant species. Root growth showed more positive response to species richness than shoot biomass under the conditions of limited watering probably because vertical separation of root systems could reduce interspecific competition. Overall survival in the 4 species mixture was not as high as the 12 species mixture and growth in the 4 species mixture tends to be less than the monoculture and the 12 species mixture. It is likely that not only species richness but the combination of different functional plant species may affect the performance of plants. The interaction between plants is very complex and this experiment might be not long enough to confirm the influence of species richness on the plant growth. Therefore, similar experiments over a longer term may be required in future research. In addition, it is also recommended to study drought tolerance of different meadow types with different diverse species.

4-3 The relationship between percentages of organic matter of substrate and plant growth in extensive green roofs

Abstract

The selection of an appropriate substrate is one of the most important factors for successful green roofs. Organic matter, which provides water holding capacity, nutrient and improves substrate structure, is generally restricted to a low percentage because it breaks down over time and leads to shrinkage of substrate. However, the percentage of organic matter tends to be decided by practitioners' experience and there have been few studies to investigate the appropriate amount of organic matter necessary for plant growth which can withstand drought on extensive green roofs. This study aimed to find out the relationship between the percentage of organic matter in the substrate and plant growth for green roofs. Different percentages of organic matter (green waste compost: 0%, 10%, 25%, 50% by volume) were added and mixed well with a commercial green roof substrate (crushed bricked based, containing less than 4% of organic matter). Four species of plants (*Allium schoenoprasum, Limonium latifolium, Melica ciliata, Nepeta x faassenii,*) were grown in trays which had 10cm of substrate with these different percentages of organic matter in a greenhouse in Sheffield, UK. There were two watering regimes: every 5 days for wet and every 15 days for dry. It was concluded that about 10% (about 14% in total because of organic matter in the original substrate) of organic matter was the best because the plants showed stable growth regardless of the watering regime. In the wet regime, increased organic matter resulted in increased growth, whereas in the dry regime, increased organic matter did not result in increased growth. This is probably because much nutrient was made available in the more frequent process of drying and rewetting of soil in the wet regime. However, the combination of high organic matter (more than 25%, about 29% in total) and the wet watering regime caused lush growth which may not be able to withstand sudden environmental changes. The response to the higher organic matter was different for different species; the species from the least responsive to the most responsive were: *Allium schoenoprasum, Melica ciliata, Limonium latifolium* and *Nepeta x faassenii.* It seemed that a species from a nitrogen rich habitat tends to be encouraged by a high organic matter content. Hence, it would be important to use an appropriate percentage of organic matter especially when nitrogen-rich habitat species are used for extensive green roofs.

1. Introduction

1.1 Characteristics of substrate required for green roofs

The selection of an appropriate substrate is one of the most important factors for successful green roofs because substrate quality (often in the absence of irrigation) is the key determinant of plant growth and success. A substrate must be designed to meet the physical, chemical and biological needs of the plants (Beattie and Berghage, 2004). An ideal substrate for extensive green roofs should have following properties:

- Efficient absorption and retention of water
- Free draining properties
- Offer a high void ratio
- Hold and make available nutrient
- Provide anchorage for plants
- Light weight
- Free from weeds as far as possible

(Kolb, 1986, Miller, 2003, Beattie and Berghage, 2004, Dunnett and Kingsbury, 2004a). This is generally achieved by granular mineral materials that absorb water and create pore spaces, mixed with fine particles (in a relatively small proportion) to which water will cling (Miller, 2003). According to Johnston and Newton (1993), an appropriate substrate for extensive green roofs would be composed of 60-70 % pore volume and 30-40 % firm substance, and incorporate 35-45 % water and 15-25 % air. Particularly suitable mineral contents includes expanded slates, expanded shale, expanded clays, baked clays, volcanic pumices, scoriae, sands, crushed clay roofing tiles and crushed brick; the remainder of the medium should be organic compost (Earth Pledge, 2005, Snodgrass and Snodgrass, 2006). Many kinds of organic matter, such as cattle, poultry and horse manure, ponderosa pine barks, redwood sawdust and peatmoss are used in the fields (Handreck and Black, 2002). However, green waste compost seems to be commonly used for green roofs.

1.2 Definition and characteristics of soil organic matter

Soil organic matter can be defined as the remains of plants and animals at various stages of decomposition, cells and tissues of soil organisms, and substances such as humus made by these organisms. Organic matter is an original slow release fertilizer. Nutrients in decayed plant materials first become a part of bodies of decomposer microorganisms. Then, as these are eaten by others, some nutrients are released as wastes. Eventually, most of the nutrients are released. Organic matter is an essential part of most growing media. The main benefits of using organic matter are summarized below (Handreck and Black, 2002).

- Binds together mineral particles of soils into aggregates, therefore it improves soil structure and the supply of oxygen and water to plants

- Source of nutrients for plants, which are released as organic matter slowly decomposes
- Helps to buffer soil against rapid changes in pH.
- Help to control root diseases, in part through a general reduction in a level of disease-causing organisms by microorganisms that are decomposing.
- Stimulate seed germination, root development and general plant growth through the plant hormone-like activity of some of its components.
- Increase an ability of plants to resist the organisms that cause diseases of both roots and shoots.

1.3 Proportion of organic matter for green roof substrate

Generally, companies provide different formulation of substrates for different types of green roofs. For example, substrates produced by Zinco (German green roof company) basically consist of crushed bricks, selected mineral aggregates and mature compost. These are combined into 4 different kinds of formulations as shown in Table 4.3.1. *Sedum* spp., which are the most commonly used for extensive green roofs, require little organic matter. As the substrate depth increases, species which need more nutrient and water are used. Hence, the percentage of organic matter and the fine granules in the substrate are increased, which increases maximum water holding capacity and therefore potentially higher saturated weight and the decrease of air content at the maximum water capacity (Alumasc exterior building products, 2006).

Table 4.3.1. The details of Zinco green roof substrate (Alumasc exterior building products, 2006)

	Extensive (Sedum)	Extensive (Rocky type plant)	Semi-extensive (Heather with lavender)	Intensive (Roof garden)
Substrate depth	Deeper →			
Plant selection	More variety →			
Granules of <0.063mm Ø	≤7 %	≤15 %	≤15 %	≤20 %
Organic content	≤4 %	≤6 %	30-40 %	50-60 %
Salt content	≤2.5 %	≤2.5 %	≤2.5 %	≤1.5 %
Porosity	63 %	63 %	64 %	64 %
pH value	7.9	7.8	7.8	7.8
Dry weight	980 kg/ m^3	980 kg/ m^3	940 kg/ m^3	930 kg/ m^3
Saturated weight	1240 kg /m^3	1330 kg/ m^3	1360 kg/ m^3	1400 kg/ m^3
Maximum water capacity	25 %	36 %	42 %	46 %
Air content at maximum water capacity	38 %	27 %	22 %	18 %
Water permeability	≥0.1 cm/s	≥0.097 cm/s	≥0.064 cm/s	≥0.034 cm/s

Many literature sources mention that organic matter should be a low proportion for green roof substrate (Miller, 2003, Beattie and Berghage, 2004, Dunnett and Kingsbury, 2004a, Snodgrass and Snodgrass, 2006). German guideline, FLL (Society of Landscape Development and Landscape Design), recommended to use 4-8% of organic matter by volume for extensive green roofs (FLL, 2002). This is because of a lack of stability; organic matter breaks down over time and leads to shrinkage of substrate. Osumndson (1999) mentioned that organic matter would decompose after 3 to 5 years and is unlikely replaced on green roofs. The speed of decomposition of organic matter depends on soil conditions such as pH, access to oxygen and sufficient moisture (Larcher, 2003). Rates of decomposition of organic materials are various and they also depend on the microclimate, but typically they progress as in Fig.4.3.1 (Handreck and Black, 2002).

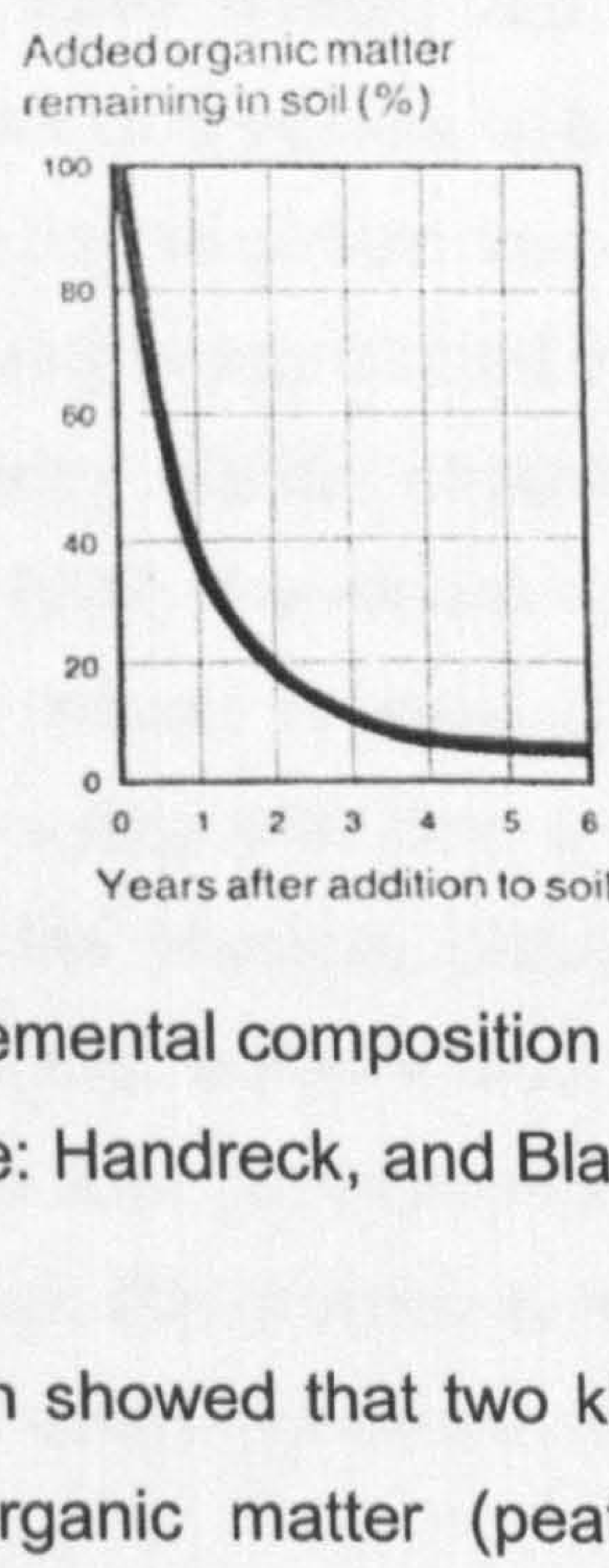


Fig.4.3.1 Typical elemental composition of humus over a year
(Source: Handreck, and Black, 2002)

An experiment in South Sweden showed that two kinds of green roof substrate which contained 3% and 10% of organic matter (peat, percentage by weight) almost completely decomposed during the first year on the roof (Emilsson and Rolf, 2005). In extensive green roofs in north England, it was observed that a substrate (containing 50% Light Expanded Clay granules, 35% green waste compost and 15% medium loam) depth decreased to half its depth after 4 years of installment because of decomposition, although most of the species grew well. However, decomposition usually results in compaction which has a big effect on plant growth. The compaction reduces the infiltration rate of water, therefore increasing surface runoff from soil, with less water in the soil for plants. It also causes a reduction in air supply to roots because of a reduction of the average size of pores. It increases soil hardness, therefore, making it difficult for plant roots to penetrate resulting in root damage. The root structure would be forced to the surface and the roots will be damaged through a lack of oxygen (Handreck and Black, 2002).Consequently, damage may take the form of plant loss through drought or water logging, poor plant or seed establishment or a general reduction in plant vigor (Kendle and Sherman, 2004). The other problems are that as organic fines decompose they create a slime, which may impede drainages causing water to build up in the media (Friedrich, 2004, Snodgrass and Snodgrass, 2006). Unless organic matter is completely decomposed it will rob the substrate of nitrogen as it completes its decomposition-this must be compensated for when using substrates that are already very low in fertility (Dunnett and Kingsbury, 2004a). Moreover, a rapid decay of organic materials may have consequences for the quality of stormwater since it might result in the leakage of nutrient to the stormwater systems (Emilsson and Rolf, 2005).

On the contrary, some studies have pointed out that the organic matter in their extensive green roofs increased as time passes, although the change of percentage of the organic matter would depend on the climate and the plant selection. A study of soil formation on green roofs in Germany demonstrated that old roofs (constructed between 1990 and 1994) had significantly higher organic matter than the young roofs (constructed between 1998 and 1999): the means were 4.6 % and 1.8 % respectively. The authors explained that the impact of initial disturbance (e.g. construction and greening insulation) decreased rapidly with time and that simultaneously, increasing synergetic processes improved the physical, biological and chemical soil properties (Schrader and Böning, 2006). Other authors also showed that the nutrient level of green roof substrate increases in time, as vegetation dies back each winter eventually to form a layer of humus, although this process is much slower than mineralization on turf or meadows at ground level where conditions are normally damper (Johnston and Newton, 1993).

1.4 The relationship between percentage of organic matter in the growing medium and plant growth

There have been some studies about the comparison between different percentages of organic matter in a growing medium on plant growth. The comparison was made of the physical properties of a pair of silt soils differing only in organic matter contents (High 2.8-3.3 %, Low 1.3-2.0 %). The more organic matter they had, the better physical properties were found relating to both plant growth and soil management. Increased organic matter gave higher water holding capacities and porosities, and decreased compaction, breaking strength and bulk densities (Hamblin and Davies, 1977). There is one study about the relationship between the formulation of inorganic materials and plant growth on extensive green roofs. Five planting substrate compositions containing 60, 70, 80, 90 and 100 % of heat-expanded slate (the remainder was mixture of 25 % sand, 10% Michigan peat and 5 % aged compost) were used to evaluate the establishment, growth and survival of two *Sedum spp.* and six taxa native to Michigan over a period of three years in the field. The result showed that no substrate composition was observed to produce consistently higher growth across all taxa. For Sedum species, moderately high levels of expanded slate (up to 80 %) can be incorporated into the growing substrate without sacrificing plant health. Although greater mortality was observed for Michigan native species, *Koeleria macrantha* could survive only in 60 % expanded slate substrate and more plants of *Coreopsis lanceolata* survived in 60 % and 70 % expanded slate than the others percentage of slate. Overall the results suggest that a moderately high level of expanded slate (70-80 %) can be incorporated into the growing substrate without sacrificing plant vigor (Rowe et al., 2006). However, the percentage of organic matter tends to be decided by practitioners' experience and there have been few studies to investigate the appropriate amount of organic matter necessary for plant growth which can withstand drought on extensive green roofs.

1.5 Research questions

This study aimed to investigate the effect of organic matter for plant growth and distinguish the appropriate percentage of organic matter for extensive green roofs. The research questions in this study are follows.

1) Does plant drought tolerance improve with a higher organic matter in the substrate?
2) Which percentage of organic matter would be the best for green roofs in terms of plant growth?
3) Do different plant species grow differently according to the percentage of organic matter?
4) How does substrate moisture content of different percentage of organic matter change over time?
5) Is there any problem of substrate shrinkage when more organic matter is added?

2. Materials and methods

To investigate the relationship between percentages of organic matter in a substrate and plant growth under wet and dry conditions, an experiment was carried out in a green house of experimental garden, University of Sheffield. The green house was chosen as an experimental site instead of a roof so that the watering regime could be controlled accurately. Different percentages of additional organic matter (0 %, 10 %, 25 %, 50 % by volume) and watering (every 5 days for wet and every 15 days for dry) were chosen as variables. Green waste compost was obtained from Hill Farm in Sheffield. The experimental substrate composed of organic matter and a commercial green roof substrate (Zinco Sedum green roof substrate, crushed bricked based, contains less than 4% of organic matter). Therefore, total percentage of organic matter was about 4%, 14%m 29% and 54% respectively. Rigid plastic open sided stacking trays (60 cm x 40 cm x 24 cm) were filled with the following components: a commercial green roof drainage layer (Zinco Floradrain) on the bottom, 10 cm plastic sheets were placed around the edges to contain the growing medium, and 8 cm of substrate (Fig.4.3.2, Fig.4.3.3).

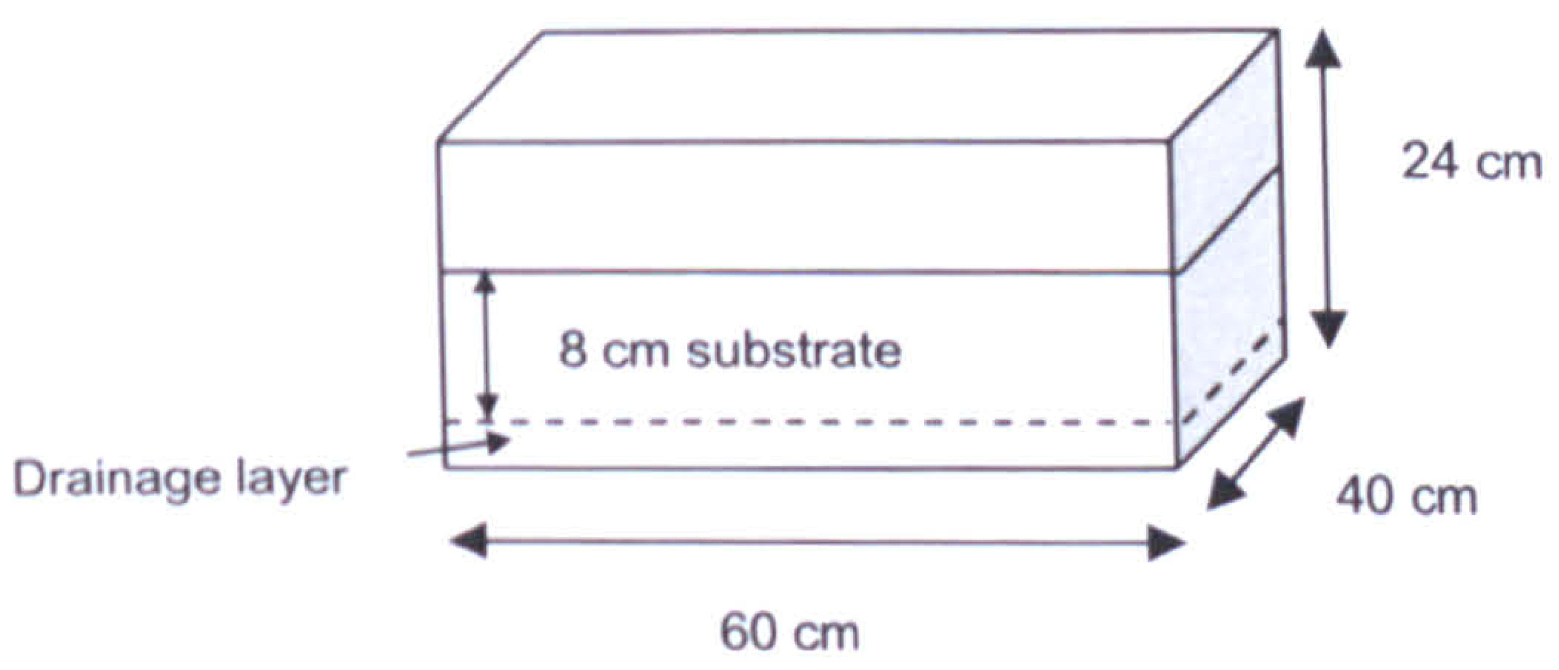


Fig.4.3.2 Component of a tray

Fig.4.3.3 Overview of a tray

Four species of plants (*Allium schoenoprasum, Limonium latifolium, Melica ciliata, Nepeta x faassenii)* were used as indicators because they are commonly used for extensive green roofs and they have different types of leaves, roots structures and habitats. Their characteristics are summarized in Table 4.3.2. Seeds were obtained from Jelitto Perennial Seeds (Schwarmstedt, Germany) and each species was sown in half seed trays which were filled with John Innes No.1 compost on 5th March 2006. The plants were transplanted to plug trays which contain 72 square cells on 7th May 2006. The plug trays were filled with Zinco semi intensive green roof substrate. On 6th June 2006, the plug plants were transplanted to the trays. In each tray, 3 plants of each species, in total 12 plants were planted randomly (Fig.4.3.4). There were 4 levels of the percentage of organic matter, 2 irrigation regimes (dry and moderate) and 3 replications, in total, 24 trays were used. Until the experiment started, the plants were watered every other day. The watering regimes were imposed on 19th July 2006. Plant growth was measured every two weeks from 24th July 2006 to 22nd October 2006, in total 7 times. Height (maximum leaf length), leaf number (shoot number was measured for *N.x faassenii*) and diameter (*L. latifolium* and *N. x faassenii* only, average of the width and length) were measured. On 22[nd] October 2002, all plants were harvested and fresh shoot weight was measured. The harvested plants were dried out in the green house until January 2007. Because of humidity in the green house, the shoots were dried in a desiccator for one week before weighing. The dry shoot weight of each plant was measured and averaged. To test for a significant difference between the treatments and the interaction, two way ANOVA (Minitab Release 14) was used. When there were significant differences, means were separated by a Tukey test at the probability level $P<0.05$.

Table 4.3.2. The characteristics of the four experimental species (Tyler, 1993, Brickell, 2003)

Plant name	Plant type	Native	Habitat
A. schoenoprasum	Bulb	Europe, Asia, N. America	Naturally found in damp meadows in the mountains, forming dense clumps
L. latifolium	Forb	Native of SE Europe from Bulgaria and Romania to S Russia	Growing in steppe and dry grassland
M. ciliata	Grass	West central Europe and Mediterranean, south-western Asia	Growing in shallow soils, typically rock areas, Limestone soils.
N. x faassenii	Shrub	A hybrid between *N. racemosa* and *N. nepetella*, species from Europe and North America	

Limonium	*Allium*	*Allium*	*Melica*
Nepeta	*Limonium*	*Limonium*	*Nepeta*
Nepeta	*Melica*	*Allium*	*Melica*

Fig.4.3.4 Example of plant arrangement
(Plants were randomly distributed in each replicate)

A second experiment measured the change of moisture over time in substrates with different percentages of organic matter. As in the previous experiment, Zinco substrate (Zinco Sedum green roof substrate, crushed bricked based, contains less than 4% of organic matter) was mixed with four levels of organic matter (0 %, 10 %, 25 %, 50 % by volume) and 9cm pots were filled with them individually. Total percentage of organic matter was about 4%, 14%, 29% and 54% respectively. There were three replications for each level of organic matter, in total, 12 pots were used. On 24th July 2006, all pots were watered well until the water started draining. After they stopped draining, 9 points of moisture in the soil (three points per pot x three pots) were measured using a moisture sensor (SM200 moisture sensor, Delta-T Devices Cambridge-England). It was measured at 18:00 every two days until 13th August 2006. The pots were watered only one time at the first time.

3. Results

3.1 Total dry shoot weight

The mean total dry shoot weight of all species in response to the percentage of additional organic matter and watering is shown in Fig.4.3.5. Organic matter, watering regime and interaction between organic matter and watering regime all had significant effects on the total dry shoot weight (Organic matter $P<0.01$,Watering $P<0.01$, Organic*Watering $P<0.05$). In the wet regime, the dry shoot weight was higher as the percentage of organic matter increased. However, in the dry regime, growth did not increase as organic matter increased. The plant growth did not show much difference in 10 %, 25 % and 50 % of organic matter, although it showed the least growth in 0 % of organic matter. In 10 % of organic matter, the difference of the amount of biomass between wet and dry regimes was smaller than in the other treatments. Therefore, substrates with 10 % organic matter would be most appropriate as green roof substrate because plant growth was stable regardless of water availability. On the contrary, in both substrates with 25 % and 50 % of organic matter, the plants in the wet regime had lush growth, however, they showed little growth in the dry regime. This difference may be potentially problematical since lush plant growth is more likely to be damaged in the dry and stressful conditions. It is more important to choose a substrate in which plants produce growth which is drought tolerant and can stand harsh rooftop environments rather than those which produce the best growth. The above explained characteristics can be seen in the pictures in Table 4.3.3.

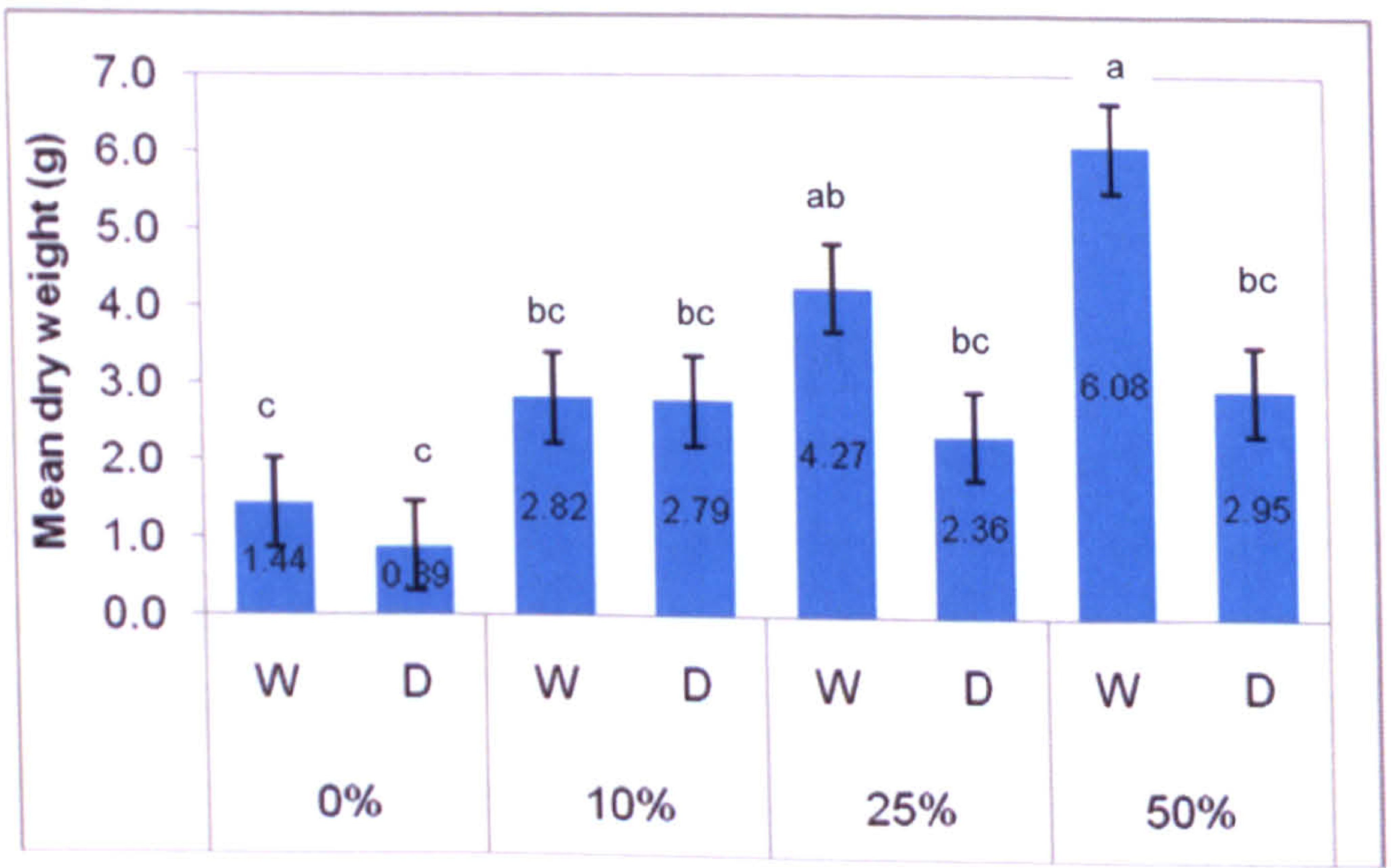


Fig.4.3.5 Total mean dry shoot weight (n=36) W=wet, D=Dry, Error bars represent standard error. Means with the same letter do not differ significantly from each other.

Table 4.3.3 Pictures of plant growth in the different percentage of organic matter and watering regime on 22nd October

0 %		10 %	
Dry	Wet	Dry	Wet
			
25 %		50 %	
Dry	Wet	Dry	Wet
			

3.2 Dry shoot weight of individual species

Mean dry shoot weight of individual species in response to the organic matter content and the watering regimes is shown in Table 4.3.4. In all species, both treatments had significant impacts on the mean dry shoot weight. In *L. latifolium*, the interaction between these two treatments also had a significant effect. Overall, the more organic matter contained in the substrate, the greater the growth in the wet regime, whereas there was not a significant difference in the dry regime. However, when dry shoot weight was analyzed by individual species, some differences became apparent. In *A. schoenoprasum,* the highest dry shoot weight was shown in 10 % of organic matter with the wet regime and it decreased as the organic matter increased. Compared to the other species, the dry shoot weight of *A. schoenoprasum* was restricted in all treatments. This is a different pattern from the other species. This is partly because *A. schoenoprasum*, which has a slender form, should be able to compete better with bigger plants such as *N. x faassenii* when organic matter increased in the substrate. In the dry regime, the shoot dry weight of *A. schoenoprasum* was the highest in 10% organic matter content. For *L. latifolium*, there was a significant difference between the results of the different watering regimes in both 25 % and 50 % of organic matter. On the contrary, in 0 % and 10 % of organic matter, there was no significant difference between the watering regimes. Particularly in 10 % of organic matter, the results in the wet and dry regime showed nearly the same amount of shoot biomass. For *M. ciliata*, 50 % organic matter content and watering had the highest mean dry shoot weight, however, the differences between the wet and dry regime in any organic matter was minor. This result suggests that *M. ciliata* did not greatly respond to the higher organic matter content. For *N. x faassenii*, the mean dry shoot weight was higher in the wet regime (except for 10 % organic matter). In this species, the difference of growth between 0 % and 50 % of organic matter was big; the result was 7 times larger in 50 % than 0 %. The response to the higher organic matter was different for different species; the species from the least responsive to the most responsive were; *A. schoenoprasum*, *M. ciliata*, *L. latifolium* and *N. x faassenii*. The growth of *A. schoenoprasum* and *M. ciliata* were not encouraged by a higher percentage of organic matter, therefore, they did not show much difference between the wet and dry regime in any percentage of organic matter. On the contrary, *L. latifolium and N. x faassenii* showed a clear difference between them as a percentage of organic matter increased.

Table 4.3.4 Mean dry shoot weight of individual species (n=9)

	0 %		10 %		25 %		50 %		SE	P
	W	D	W	D	W	D	W	D		
A. schoenoprasum	0.27ab	0.22b	0.44a	0.34ab	0.36ab	0.25ab	0.29ab	0.23ab	0.05	O<0.05 W<0.05
L. latifolium	2.16b	1.41b	2.48b	2.29b	5.78a	2.73b	7.22a	3.04b	0.57	O<0.01 W<0.01 O*W<0.01
M. ciliata	1.11b	0.59b	1.18b	0.85b	1.30b	0.92b	2.31a	1.42ab	1.11	O<0.01 W<0.01
N. x faassenii	2.20c	1.34c	7.18b	7.67b	9.64b	5.51bc	14.48a	7.09b	0.99	O<0.01 W<0.01

SE=Standard Error, P=Probability, W=Wet, D=Dry, O=organic matter regime, W=watering regime, O*W=interaction between organic matter regime and watering regime, Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

3.3. Growth of individual species

The change of growth from 24th June to 22nd Oct (height, leaf or shoot number, diameter) are shown in Table 4.3.5 and Table 4.3.6 respectively. In Table 4.3.5, only probability from the results of statistical analysis and in Table 4.3.6, the mean final growth of individual species is shown. For most species, organic matter content affected growth significantly from the beginning whereas the watering regime started to have an effect later, after 50 days. A possible reason for this is that the plug plants were transplanted to the substrate with the different percentage of organic matter 44 days before the different watering regimes started. Overall, the results showed that plant size was significantly small in 0% of organic matter especially in the dry regime.

Therefore, this is too small to be desirable in practice. On the other hand, in 50 % of organic matter, the plants may be too big to tolerate drought and damage in the green roof environment, especially *L. latifolium* and *N. x faassenii.*

Table 4.3.5 Growth change of individual species over time (The result shows only probability from the results of statistical analysis)

		24th June	10th July	23th July	6th August	21st August	18th Sep	22nd Oct
	Days after start watering regime	5	23	36	50	65	93	127
A. schoenoprasum	Height	O<0.01	O<0.01	O<0.01	O<0.01	O<0.01 W<0.01 O*W<0.05	O<0.01 W<0.01	O<0.01 W<0.01
	Leaf number	ns	ns	ns	ns	ns	ns	ns
L. latifolium	Height	O<0.01	O<0.01 O*W<0.05	O<0.01 O*W <0.01	O<0.01 W<0.05 O*W <0.01	O<0.01 W<0.01 O*W <0.01	O<0.01 W<0.01 O*W <0.01	O<0.01 W<0.01 O*W <0.01
	Leaf number	ns	ns	ns	O<0.01 W<0.01	O<0.01 W<0.01	W<0.01	W<0.05
	Diameter	-	-	O<0.01 O*W <0.01	O<0.01 W<0.01 O*W<0.01	O<0.01 W<0.01 O*W<0.01	O<0.01 W<0.01 O*W<0.01	O<0.01 W<0.01 O*W<0.01
M. ciliata	Height	O<0.01 W<0.05	O<0.05	O<0.01	O<0.01 W<0.05	O<0.01 W<0.01	O<0.01 W<0.05	O<0.01 W<0.05
	Leaf number	W<0.05	O<0.01	O<0.01	O<0.01 W<0.05	O<0.01 W<0.01	O<0.05 W<0.05	W<0.05
N. x faassenii	Height	O<0.01	O<0.01	O<0.01	O<0.01	O<0.01 W<0.01 O*W<0.05	O<0.01 W<0.01 O*W<0.01	O<0.01 W<0.01 O*W<0.05
	Shoot number	-	-	O<0.01 O*W <0.01	O<0.01	O<0.01 W<0.01 O*W<0.05	O<0.01 W<0.01 O*W<0.01	O<0.01 W<0.01 O*W<0.01
	Diameter	-	-	O<0.01 O*W <0.01	O<0.01 W <0.05	O<0.01 W <0.01	O<0.01 W<0.01 O*W<0.01	O<0.01 W<0.01

O=organic matter regime, W=watering regime, O*W=interaction between organic matter regime and watering regime.

Table 4.3.6 The mean final growth of individual species on 22[nd] October (n=9)

	Organic matter	0 %		10 %		25 %		50 %			
	Watering regime	W	D	W	D	W	D	W	D	SE	P
A. schoenoprasum	Height	30.78 c	21.78 d	39.41 ab	34.9 bc	37.24 abc	31.74 c	42.97 a	31.9 c	1.67	O<0.01 W<0.01
	Leaf number	8.78 a	8.78 a	10.56 a	10.44 a	9.44 a	9.11 a	9.44 a	9.22 a	1.09	ns
L. latifolium	Height	9.66 d	8.01 d	13.49 c	11.62 cd	18.58 b	11.47 cd	22.22 a	13.84 c	0.82	O<0.01 W<0.01 O*W<0.01
	Leaf number	15.56 ab	13.44 ab	13.33 ab	11.56 b	16.89 a	12.56 ab	12.33 ab	12.00 ab	1.16	W<0.05
	Diameter	17.48 b	14.19 b	20.77 b	17.29 b	26.63 a	17.71 b	30.94 a	20.39 b	1.16	O<0.01 W<0.01 O*W<0.01
M. ciliata	Height	39.96 a	37.24 a	42.72 a	39.51 a	44.52 a	39.33 a	47.52 a	40.38 a	2.84	W<0.05
	Leaf number	58.89 c	37.44 c	66.78 bc	55.44 c	73.22 bc	73.89 bc	140.78 a	115.89 ab	11.65	O<0.01 W<0.05

N. x faassenii	Height	29.68 de	21.54 e	43.87b c	31.43 cde	46.52 b	32.92 bcde	64.63 a	38.37 bcd	3.11	O<0.01 W<0.01 O*W<0.05
	Shoot number	27.67 b	22.89 b	56.78 b	64.44 b	112.00 a	60.00 a	147.67 a	54.89 b	10.36	O<0.01 W<0.01 O*W<0.01
	Diameter	22.46 cd	18.11 d	34.77 ab	28.42 bcd	35.30 ab	28.93 bc	43.86 a	30.09 bc	2.39	O<0.01 W<0.01

SE=Standard Error, P=probability, O=organic matter regime, W=watering regime, O*W=interaction between organic matter regime and watering regime. Letters of Tukey multiple comparison are compareing values within a row. Means with the same letter do not differ significantly from each other.

3.4 Moisture in the substrate

The result showed that the organic matter content significantly affected moisture in the substrate and it increased as organic matter increased (Fig.4.3.6, Table 4.3.7). It was confirmed that the substrate with higher organic matter was able to maintain higher moisture levels. The moisture content in the substrate with 50 % of organic matter was significantly higher than the others whereas in 0% it was significantly lower. There was no significant difference between 10 % and 25 % of organic matter. The moisture content dropped quickly after watering in the low percentage of organic matter in the substrate. In 0 % of organic matter, the moisture content decreased from 22.28 % to 5.20 % in next two days, whereas in 50 % of organic matter, they showed more than 5 % after 20 days.

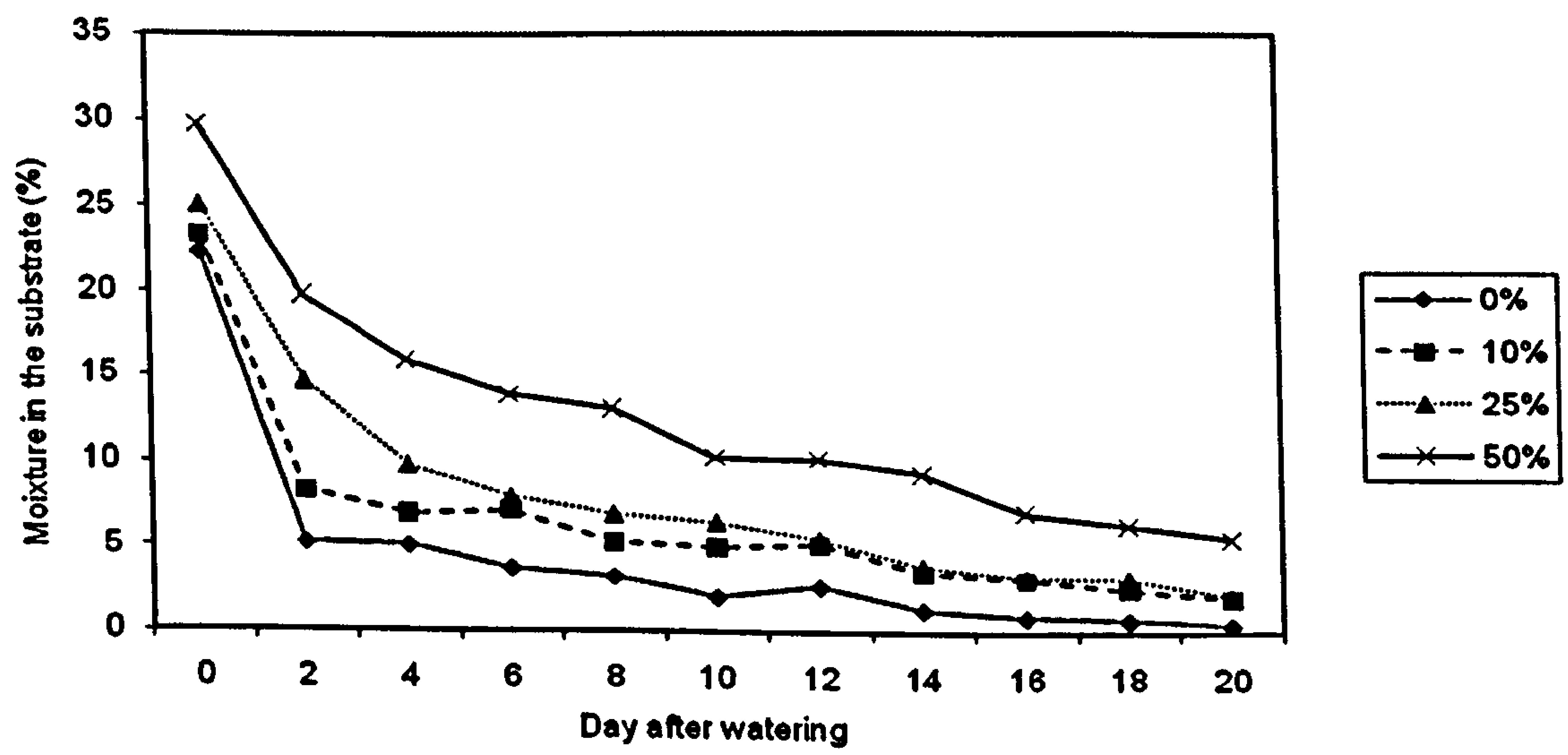


Fig 6 Change of percentage of moisture in the substrate over time

Table 4.3.7 Change of percentage of moisture in the substrate over time

		Days after watering										
		0	2	4	6	8	10	12	14	16	18	20
Percentage of organic matter	0 %	22.28 b	5.20 c	5.06 c	3.72 c	3.22 c	2.01 c	2.66 c	1.30 c	0.88 c	0.70 c	0.43 b
	10 %	23.27 b	8.24 c	6.98 bc	7.20 b	5.30 bc	5.03 b	5.16 b	3.50 bc	3.14 b	2.54 bc	2.03 b
	25 %	25.12 ab	14.78 b	9.90 b	8.01 b	7.02 b	6.57 b	5.56 b	3.98 b	3.32 b	3.22 b	2.17 b
	50 %	29.69 a	19.82 a	16.00 a	14.03 a	13.21 a	10.37 a	10.28 a	9.38 a	7.11 a	6.33 a	5.58 a
	SE	1.53	0.82	0.81	0.73	0.65	0.65	0.58	0.67	0.50	0.52	0.49
		P<0.01	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01	P<0.01

SE=Standard Error, P=probability Letters of Tukey multiple comparison are compareing values within a colum. Means with the same letter do not differ significantly from each other.

4. Discussion

4.1 Effect of watering

Overall, in the wet regime, the higher organic matter the substrate had, the greater increase in growth the plants showed. This may be a result of improved nutrient availability as the organic matter increased. Organic matter decomposition, which is accompanied by nitrogen mineralization, occurs in a process of drying and rewetting of soil (Sorensen, 1974, Kieft, et al., 1987, Denef et al., 2001). Mineralization of organic phosphorus can also occur but probably to a much smaller extent and in this instance fixation by the soil can take place. The amounts of bases and trace elements (e.g. manganese) that go into solution are also affected by drying (Birch, 1958). The higher organic matter may improve the soil structure and the ability of the soil to accept water and drain well through massive production of polysaccharides. This is the one of the key materials that bind soil particles together into aggregates, which are essential parts of improved soil structure (Handreck and Black, 2002). On the contrary, overall growth did not increase with organic matter content in the dry regime, although the soil moisture content was higher. The reason might that the process of drying and rewetting of soil would be less and decomposition was not much encouraged. Hence, the nutrient availability was reduced compared to the wet watering regime even with high organic matter. On a roof, the rainfall is frequent, especially in the UK. This would be associated with a greater frequency of the drying and wetting cycle and lush growth in the high organic matter could be predicted.

4.2 Effect of organic matter

It was concluded that about 10% (about 14% in total) of the organic matter was the optimal figure because the plants showed stable growth regardless of the watering regime. On the contrary, use of 0 % (about 4 % in total) of the organic matter was not recommended because growth was restricted even though they had enough water.

This may be because that soil that is low in organic matter will exhibit nitrogen deficiency (Kendle and Sherman, 2004). This result agreed with previous studies. In the study of Pennsylvania State University, it was shown that approximately 20 % organic matter and 80 % inorganic appeared to be the best mix in terms of plant growth response to date (Beattie and Berghage, 2004, Mather, 2006). In another study, which was explained in the introduction, 100 % of expanded slate generally exhibited the lowest visual ratings for both of Sedum and Michigan native species (Rowe et al., 2006).

It is suggested that more than 25 % organic matter (about 29 % in total) was not recommended for extensive green roofs from the point of plant growth. The environment of the green roof tends to be drier and more exposed than on the ground. However, continuous rain or high irrigation in high organic matter substrate, lush plant growth would be encouraged which may result in damaged during drought. Plants grown with an abundance of all their requirements will be soft, and will lack an ability to withstand the sudden environmental stress (Handreck and Black, 2002). As organic matter become older, the rate of decomposition is too low to provide enough nutrient, therefore, additional organic matter or fertilizer might be necessary to maintain vigorous plant growth. There is some benefit to having moderately stressed plants on green roofs. Plant roots grow into the substrate and they extract water from deeper in the substrate. The end result of the moderate stress imposed by this strategy is more efficient use of the substrate and its stored water and nutrients. Hardier plants can be produced if water and nutrient are carefully limited to a little below the amounts needed to produce lush growth (Handreck and Black, 2002). Species which are commonly used for green roofs are tolerant of poor substrates and relatively thin soils help them to compete with more vigorous species which prefer richer soils (Johnston and Newton, 1993) and they also reduce weed growth.

4.3 Growth of individual species

The response to the higher organic matter was different for different species; the species from the least responsive to the most responsive were; *A. schoenoprasum*, *M. ciliata*, *L. latifolium* and *N. x faassenii*. This difference could be explained by nutrient condition in their typical habitats. Elberse and Berendse (1993) studied growth of eight perennial grass species from habitats with contrasting soil fertilities in a green house. The species were ranked according to the nitrogen number proposed by Ellenberg (1998), which indicates the relative nitrogen availability in the habitats in which these species frequently occur. The result showed that the nutrient-rich habitat species produced more shoot biomass than the nutrient-poor habitat species in both nutrient-poor and rich conditions, although the difference was smaller in the nutrient-poor conditions. The Ellenberg nitrogen values of the species which were used in this experiment are *A. schoenoprasum* 2, *Limonium* spp. 3-5, *Melica* spp. 3-5, and *Nepeta* spp. 7-6. The smaller value indicates that their natural habitats tend to be poorer in nutrients. This supports the result in this experiment; the species which come from rather nutrient-rich habitats produced more shoot biomass in any percentage of organic matter and they grew particularly better in the higher organic matter. Hence, it would be important to use the appropriate percentage of organic matter especially when the nitrogen-rich habitat species are used for extensive green roofs.

5. Conclusion

It was shown that a certain amount of organic matter is essential and 10 % (about 14 % in total) organic matter was the best to get the stable plant growth regardless of the watering regime. The combination of high organic matter (more than 25 %, about 29 % in total) and the wet watering regime caused lush growth which may not be able to withstand sudden environmental changes. In the wet regime, the more organic matter the plants had, the greater growth increase they showed. On the contrary, in the dry regime, the growth did not increase as the organic matter increased. This is probably because more nutrient was made available in the more frequent process of drying and rewetting of soil in the wet regime. The response to the higher organic matter was different for different species; the species from the least responsive to the most responsive were: *A. schoenoprasum*, *M. ciliata*, *L. latifolium* and *N. x faassenii*. It seemed that the species from nitrogen rich habitats tended to have larger shoot biomass and their growth was encouraged by high organic matter. Hence, it would be important to use the appropriate percentage of organic matter especially when the nitrogen-rich habitat species are used for extensive green roofs. In this study, shrink of the substrate was not observed after 6 months of the establishment. However, the decomposition of organic matter is more likely on the roof rather than in the green house because of frequent rain and exposure. Future research would be required to observe how the shrinkage of substrate would affect plant growth in both a green house and roof over a period of years. In addition, more detailed studies of physical and chemical properties of different kinds of organic matter would be useful for future research.

Chapter 5 Intensive one year case study

Investigation of dynamic cycles of semi-extensive green roof

Abstract

The phenological study of green roofs (e.g flowering performance and growth pattern over a year) has been limited although it is crucial to create aesthetic and seasonal interesting green roofs. This study aimed to investigate the dynamic cycle of semi-extensive green roofs. To achieve this aim, the following four points were studied on the green roof of Moorgate Crofts Business Centre Rotherham, UK from February to November 2006: (1) Characteristics of seasonal change (2) Individual plant growth pattern and flower performance (3) Planting design (effect of plant species diversity and planting density, aspect) (4) Maintenance (weeds invasion and self-seeding). This green roof was installed in the summer 2005 and 54 species of perennials, ornamental grasses and bulbs were planted at 10 cm (areas with gravel mulch) and 20 cm (areas without mulch) of substrate. 32 places of quadrates (50 cm x 50 cm) were set up by the combinations of plant species diversity (High and Low), planting density (High and Low), aspects (South East, South West, North East, North West) and covering gravel mulch (with and without). The percentage of coverage, plant height, flower succession, number of weeds invasion and self-seeding were measured. The result showed that it was possible to create aesthetic extensive green roof which has long flowering and seasonal interest with little maintenance and supplemental irrigation if appropriate plants were chosen. Except for *Sempervivum arachnoideum* and *Sedum spathulifolium*, var. *purpureum* all plant species used in this study showed good growth and flower performance. Throughout 9 months, at least 3 species flowered in each month and the highest number of flowering species was observed in June. *Silene uniflora, Erodium ciliatum, Sedum kamtschaticum* var. *floriferum* 'Weihenstephaner Gold' and *Calamintha nepeta* showed particularly long flowering performance. It was shown that plant species diversity might affect overall flowering succession and dynamic change and planting density might affect interaction between plants. In areas of high plant species diversity, there were more possibilities to have a longer flowering term, more seasonal interest and dynamic change than low plant species diversity. In areas of low planting density, individual plants generally produced the better growth than those in high planting density. Moreover, the plant growth had more interaction between species in the higher planting density. However, these tendencies were not only because of the difference of plant species diversity and planting density itself but they were affected strongly by the combination of species which were used. Therefore, it is important to be aware of individual growth characteristics such as plant size (coverage

and vertical), phenological growth pattern and flowering season. There was no significant difference between aspects in both of plant growth and flower performance. However, the tendency was observed that the plants had better growth in the NE and the SE. Also, longer flower duration was shown in the NW whereas many species started flower from the SE. It is worth noticing that the reaction for different direction was different from plant species. Only 9 species of weeds were found on this green roof. The total number of weeds decreased from August, therefore, Spring-Summer weeding is particularly important. The combination of low plant species diversity and high planting density could reduce weeds effectively. The high frequency of weeds was found in the NW whereas the number of weeds was smaller in the SE probably because of wind direction. Using a gravel mulch in shallow substrate could reduce the number of weeds significantly. Many species used in this study were self-seeding and *Allium schoenoprasum, Campanula rotundifolia, Festuca* spp. and *Petrorhagia saxifraga* showed very high number of seeding. *Erodium manescavii, Euphorbia cyparissias* 'Fens Ruby' and *Festuca* spp. established well and grew fast and these species could be invasive. Such information would be useful for selection of plant species, planting design and maintenance for further extensive green roof instalment.

1. Introduction

1.1 Phenology of extensive green roofs

Previous plant selection studies for green roofs tend to be focused on species survival, their growth and colonization (e.g. Koehler, 2003, Monterusso, et al., 2005, Koehler, 2006) rather than aesthetic and seasonal interest over time. Of course, survival would be the priority in the severe environment of an extensive green roof and phenological study (Phenology-periodic biological events as influenced by the environment, Shwartz, 2003) may be not necessary if *Sedum* spp. are used since usually they produce uniform vegetation layers and have only a limited term of flower performance. Vegetation of spontaneous green roofs (Brown roofs) may have dynamic change, however, the majority of research of spontaneous vegetations might be related to the sequential changes in plant populations subsequent to previous colonization (Burrows, 1990). Semi-extensive green roofs and intensive green roofs allow the growing of more species and they have greater aesthetic value. They have some similarities to gardens on the ground; attributes of plants dynamic cycles of spring emergence, growth and autumnal decline, sometimes attractive foliage and architecture, and frequently, attractive flowers (Hitchmough,1995). Phenology of species, i.e. growth pattern through growing seasons, can be a crucial factor in creating compatible mixtures of species that have a long season of display (Dunnett, 2004b). The planting might have greater compatibility in terms of growth rate and growth habit that could promote greater species diversity. The fact of knowing the phenology of plants may be possible to formulate mixes for plants with continuous flowering periods and attractive color combinations and leaf textures (Kircher, 1998). Although the role of individual species must not be neglected, it is the functioning of entire vegetation patches, plant communities or ecosystems that is being considered (Burrows, 1990). However, a limited study of dynamic change on green roofs has been carried out. There is one study of the dynamics and visual impact of planted and colonising species on a green roof (Dunnett and Nagase, 2007). During each growing season, the mean height and spread of fifteen herbaceous perennial grass and herb species was recorded, together with flowering performance and % vegetation cover. Another example is a long term study from 1986 to 2005 by Koehler (2006) and number of vascular plants, percent coverage of each species, plant heights and the percentage of standing dead (living plants with dead leaves and stems) were measured in two green roofs.

1.2 Characteristics of potential plant species for extensive green roofs

Potential herbaceous perennials for extensive green roofs (up to 20cm of substrate) could be divided into five categories (Dunnett and Nolan, 2004, Dunnett, 2004a).

- Low growing species, either creeping or clump forming. Such species are typical of extensive green roofs and generally severe to form a complete ground cover (e.g. *Sedum acre*, *Armeria maritima* 'Alba', *Dianthus deltoides*)
- Medium height clump forming species. These species were intended to provide structural and visual diversity to the plantings (e.g. *Calamintha nepeta, Limonium platyphyllum, Salvia* x *sylvestris* 'Blue Queen')
- Taller 'emergent' species. These species were intended to provide structural and visual diversity to the plantings (e.g. *Gaura lindheimeri, Kniphofia* 'Border Ballet')
- Grasses. The grasses provide evergreen components to the plantings and severe to unify the plantings, providing a naturalistic, meadow-like character (e.g. *Festuca glauca, Festuca scabiosa*)
- Bulbs. These species starts flowering earlier than other perennial species (e.g. *Muscari armeniacum, Tulipa tarda*)

The above plant groups have been used for extensive green roofs and many publications included their plant list (e.g. Toronto City Hall; Pearce. 2003, The Peggy Notebaert Nature Museum; Dvorak, 2003). However, there was a tendency that these reports did not mention which species were successful in survival, growth and flower performance after instalment of green roofs. An exception is the study by Hauth and

Liptan (2003), which showed the detail observation of 28 plant species on Hamilton Apartment roofs in Portland Oregon (US) although the scientific figures (e.g. height, length of flowering) and specific flowering periods were not included.

1.3 Plant species diversity and planting density

The importance of high species diversity in terms of productivity, stability and survival was mentioned in Chapter 4 (Drought tolerance study). In this chapter, dynamic change and aesthetic including overall flower succession which might be affected by plant species diversity are particularly paid attention. While simple low-plant species diversity plantings work well in more formal settings where there are requirement for neatness, order and productivity (Dunnett, 2004b), more complex mixtures may contain a variety of forms to enhance the visual and structural diversity of the planting and well-chosen mixtures provide diversity of form and colour but also offer a long flowering season as one set of plants takes over from another (Dunnett and Kingsbury, 2004a).

According to Hassell and Coombes (2007), average planting density of extensive green roofs using plug plants is 15-20 plants per m^2. Planting spacing or planting density has a significant impact on longevity, survival, height, resistance to drought tolerance (Hitchmough, 2004a). However, little is known about plant growth in different planting density on extensive green roofs. Hitchmough (1994a) summarized the likely effects of planting density on herbaceous perennials as follows. 1) As planting density increases, individual plants will grow less large, although the total amount of standing vegetation is much the same across a wide range of planting densities. 2) As planting density increases, competition between individual plants in a grouping for finite resources such as water, nutrients and light becomes more intense. 3) Within a block of a particular species the bare soil will be covered by foliage more quickly in spring.

1.4 Aspect

Aspect may affect plant growth because of different sunlight, temperature, water availability and wind direction. Some previous studies showed that the plant growth was better in the north than the south on a roof probably because of harsh environment in the south of the roof in the summer. According to Werthmann (2007), the south terrace was consistently hotter with an average temperature of four degrees than other terraces on the roof of the ASLA headquarters building in Washington D.C during June to August 2006. Koehler(1990) compared the microclimate of a different direction of roof and showed the aspect affect the plant growth significantly on the roof. The richest spectrum of species was observed on the north side with 60 species (48.4 g/ m^2 biomass May-September), compared to 38 species (18.3 g/ m^2 biomass) on the south side. Green roofs tend to have high exposure because of open place, high wind and thin substrate, therefore, it was estimated that plants would grow better in light shade direction. Indeed, Kolb (1995) showed that in light shade a somewhat larger number of species survives over a period of several years-presumably as a result of reduced water stress.

1.5 Weeds colonization

There is a high likelihood that wind-blown seeds will find their way onto the roof and establish. Tree and shrub self-seedlings are a particular problem because of the danger of their roots damaging the underlying roof membrane. Other problem species are wind-dispersed annuals that can gain a toehold, grow and set seed rapidly, and contaminate the rest of the vegetation (Dunnett and Kingsbury, 2004a). Therefore, early and regular weeding is critical. During establishment of green roof, weeding must occur over a period of months to control the varied weed species (Snodgrass and Snodgrass, 2006). An understanding of weed phenology and population dynamics can guide the choice of timing of weed control practices and the life history stages to target (Holt, 2004). However, little is known about weed science studies for green roofs. There are some long term studies of plant colonization for extensive green roofs (e.g. Koehler, 2003) however, they have been focused on the change of plant population on spontaneous green roof rather than weeds invasion on planted species of green roofs. A notable exception is Dunnett et al (2007) who undertook detailed analysis of weed invasion on a green roof in Sheffield over the period of 6 years. The main conclusions of this study were that although over 30 different species of weeds were found, the vegetations were dominated by just a small number of these, leading to spontaneous communities with low plant diversity. There was some evidence that the shallower substrates promoted greater weed diversity than deeper substrates.

It is important to understand methodologies to reduce weeds invasions for low maintenance. Opportunities for weed colonization can be reduced by using large blocks of the same species planted at high densities. Morphological factors such as canopy depth (height) and planting density (in terms of light interception) across the year, and the capacity of spent foliage to self-mulch in winter are also very important (Hitchmough, 1994 a). Dunnett and Kingsbury (2004a) mentioned that achieving continues vegetation cover reduces the space available for unwanted plants to establish. Plant species diversity may also affect weeds invasion through two principles 1) Plant species diversity is good an often diminishes harmful interference. 2) Filling all ecological niches diminishes competition (Dunnett, 2004b, Zimdahl, 2004). Mulches can restrict weed colonization and prevent weed seed germination by excluding light.

They also have advantage of reduction of evaporation from soil surface and aesthetic value. Good mulching material for ornamental includes wood or bark chips, sawdust, peat-moss, small grain straw free of weed seeds, pine needles and gravel or stones (Klingman,et al., 1982). It seems that bark mulch (usually, glue is mixed with bark mulch to prevent to be blown away) is commonly used for green roofs in Japan (e.g. Tokyo Metropolitan government green roof).

1.6 Self-seeding

Some of species which are commonly used for green roofs can be self-sowing: they disperse seeds freely and the seeds germinate quickly. For example *Allium* spp. self-sow well while slow to establish (Dunnett and Kingsbury, 2004a). Self-seeding can either be valuable or a problem trait, depending upon situation (Hitchmough, 2004c). In meadow planting, self-seeding may be recommended to fill the gap, however, if they displace the other plants, it could be problem. Plant establishment from vigorous self-sown seed can be minimized by 1) using species that do not produce viable seed in Britain or require high temperature for germination and 2) cutting before seed is physiologically capable of germination (Hitchmough, 1995)

1.7 Research questions

In this chapter, the phenology of individual species (growth and flowering) and colonization (weeds and self-seeding) over a year were studied on one green roof. The research questions of this study are follows.

1) How do plant species perform in mixed, semi-extensive vegetation?
2) What is the length of flowering display of mixed herbaceous vegetation on a green roof?
3) Are the plant growth and flowering term different from aspects?
4) How do height and coverage of vegetation change over time in different plant species diversity and planting density?
5) How does plant species diversity and planting density affect the weed and self-seeding invasion?
6) Which weeds are commonly observed on the roof?

2. Materials and methods

To answer the questions raised above, the dynamic change of a semi-extensive green roof on Moorgate Crofts Business Centre in Rotherham (North England, Latitude-53.4332, Longtitude-1.3557) was studied from February to November 2006. The experimental site is on the fourth story of a commercial building. Two types of green roofs were installed in the summer 2005; the upper roof- 5 cm substrate and sedum mat (185 m^2not accessible, design load 100kg/m^2) and lower roof –10 cm (area with gravel mulch) and 20 cm (area without mulch) of substrate planted with perennials, ornamental grasses, bulbs and alpines (415 m^2, Accessible, design load 305 kg/ m^2). In this experiment, only the lower green roof was used. The semi-extensive green roof consisted of Hi-Ten Universal vapour barrier, 9 cm Alumasc BGT polyurethane insulation, Durbigum water proofing membrane with Preventol B2 root barrier, Moisture mat SSM45, Floradrain FD 40 drainage layer, Filter sheet SF and 20 cm Zinco' Heather with Lavender substrate. In alpine planting area, 2.5cm of gravel mulch over 10cm Zinco Heather with Lavender substrate was used. Underneath of substrate, 7.5 cm Zincolit (crushed brick) was used to make up levels. All materials were obtained from Alumasc (Merseyside, UK). The plants types used were 40 % of UK native plant species and 60 % of non-native species. The plant list is follows.

Perennials and alpines:

Allium schoenoprasum

Armeria juniperifolia

Armeria maritima 'Splendens'

Aster amellus

Calamintha nepeta

Campanula rotundifolia

Centaurea scabiosa

Dianthus deltoides

Erodium ciliatum

Erodium manescavii

Euphorbia cyparissias 'Fens Ruby',

Galium verum

Geranium cinereum 'Ballerina'

Geranium endressii 'Wargrave Pink'

Geranium lucidum

Gypsophila repens 'Dorothy Teacher'

Helianthemum nummularium 'Wisley Primrose'

Helictotrichon sempervirens

Kniphofia 'Border Ballet'

Lavandula angustifolia 'Hidcote'

Leucanthemum x superbum

Limonium latifolium

Nepeta x faassenii

Origanum laevigatum 'Herrenhausen'

Petrorhagia saxifraga

Phlox douglasii

Primula veris

Pulsatilla vulgaris

Salvia x sylvestris 'Blauhügel'

Sedum acre 'Golden Queen'

Sedum album 'Coral Carpet'

Sedum 'Herbstfreude'

Sedum hispanicum 'Silver Carpet'

Sedum kamtschaticum var. *floriferum* 'Weihenstephaner Gold'

Sedum reflexum (standard form)

Sedum sexangulare,

Sedum spathulifolium -var. purpureum

Sedum spurium 'Green Mantle'

Sedum telephium 'Matrona'

Sempervivum arachnoideum

Silene uniflora

Sisyrinchium striatum

Stachys byzantina 'Silver Carpet'

Verbascum phoeniceum

Grasses:

Festuca amethystina

Festuca glauca

Melica ciliata

Stipa tenuissima

Bulbs:

Allium caeruleum

Allium karataviense

Crocus tommasinianus 'Whitewell Purple'

Muscari armeniacum

Tulipa tarda

Tulipa praestans 'Fusilier'

These plants were obtained from Chapel Cottage Plants (Cambridgeshire, UK), Van Dogeweerd (Lincolnshire, UK), Barbara Austin Perennials (Wiltshire, UK), Gedney Bulbs (Lincolnshire, UK), Mike Handyside Wildflowers (Cheshire, UK) (Griffith, 2006). The roof is designed to look good throughout the year, with special emphasis on ensuring the winter appearance was attractive. Grasses are used to give winter interest, and many of the plants have attractive seed heads and the plantings are not cut back until late winter. Gravel mulches also provide winter patterning. The plants were chosen to have long flowering. To start with early flowering species such as *P. veris* and bulbs, in March and April. In May the roof is dominated by *A. schoenoprasum*, whilst in June and July many of the native wildflowers make a strong contribution. Prominent species include *C. scabiosa* and *G. verum*. In the late summer and *A. amellus* and the late flowering taller sedums carry on the display, together with the ripened grasses. The grasses are particularly important in providing a setting for the flowering plants: *S. tenuissima* is used prominently. There was no formal planting plan. Instead three planting mixes were used in broad sweeps: A: semi-extensive mix, B: alpine mix, and C: low-edge mix which combined elements of the two (Fig.5.1, attached at the end of this chapter). The planting density of each area was 18 plants/m^2, 22 plants/m^2 and 18 plants/m^2, respectively. Within these mixes, each species was planted in groups of 5-10 individuals, but those groups were randomly arranged within the areas by the contractor, giving a very spontaneous appearance. The overall appearance and effect is of repetitive waves of colour as each species and group of species comes into flower (Li, 2007). A leaky pipe irrigation system was installed to assist with initial establishment, and to provide a source of water in the event of a prolonged or severe drought. This was used to refresh the planting after the sustained high temperatures in July 2006. Weeds were removed regularly (6times in 2006, in late February, 19 May, 11 July, 5 August, 11 September, and 12 October). In this study, the following four studies were carried out from February to November 2006.

2.1 Overview

To investigate the seasonal change and continuity of flowering and visual quality, photographs were taken from the same position in four directions in every two weeks. These four positions (P1-P4) are shown in Fig.5.1. (attached at the end of this chapter)

2.2 Plant species performance

The main focus of the work was to investigate plant performance: flowering time, plant growth and the effect of aspect (whether facing NE, NW, SE and SW). Therefore 12 representative plants (4 planting aspects x 3 replications) of all species were randomly chosen and they were marked by flags. These selected plants were measured for both of flowering time and growth.

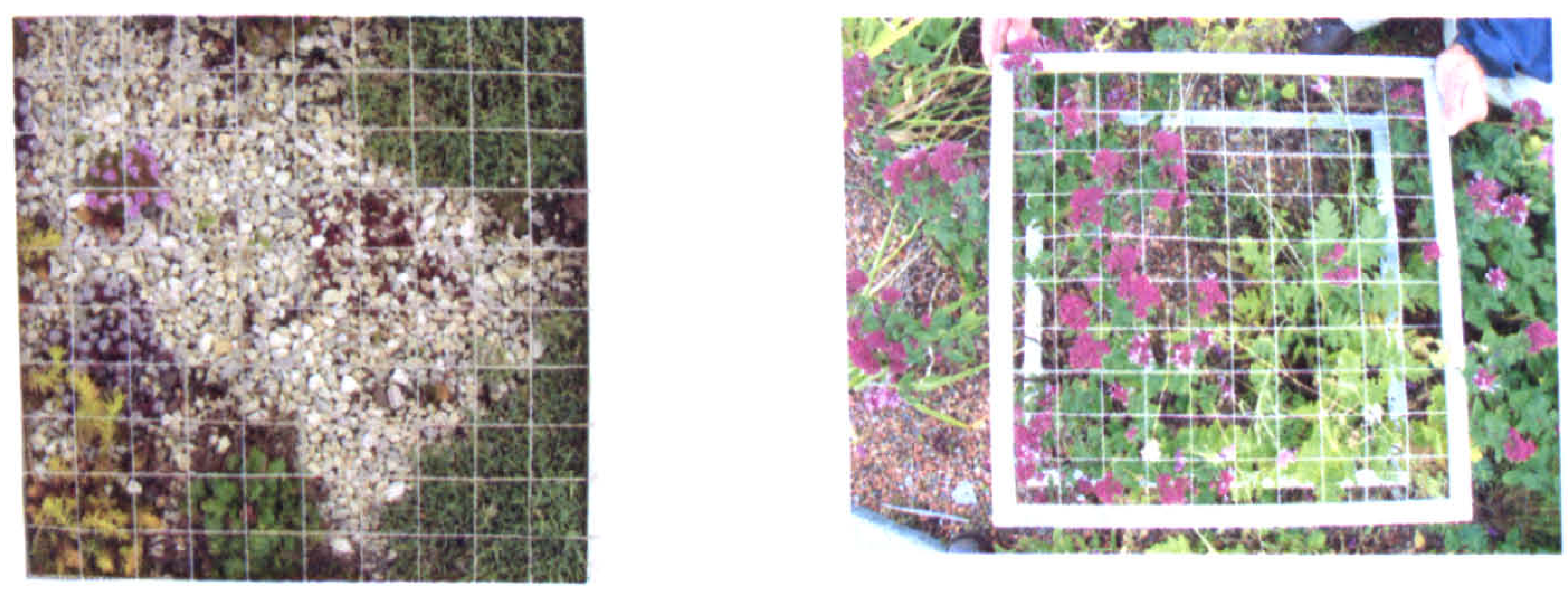
Flowering time was studied every two weeks from February to November 2006. When more than one plant of a species was flowering, the following three parameters of all 12 representative plants were measured and averaged. The parameters were (1)

Flowering shoot number (2) The relative appearance, on a 1 to 5 scale: 1= Only little number of flower is observed and still they have weak flower impression. 2= About 20% of shoots have flowering, however, impression is still weak 3= Half of shoots have flowering and visual impression is moderate 4= About 80% shoots have flowering and visual impression is good 5= Plants are in full bloom, with high visual quality (3) Percentage of flowering plants number within 12 representative plants (Number of flowering plants/12 x100 %).

Because a large number of species were involved, plant growth was measured only once in September. This season was chosen because by then most of species had reached their maximum growth. All species except bulbs were measured in these 5 parameters (1) Mean height (flower height) (2) Diameter (average of width and length) (3) Flower shoot number. If they had flower stems although they finished flowering, the length of flower stem was measured.

2.3 Quadrat study

Quadrats have been widely used in plant ecology studies, and can be used to map stands of plant communities according to their visual compositions and to enable the recording of spatial and temporal change (Gracia-Albarad, 2005). The size of quadrat used was 50 cm x 50 cm and it was divided into a 5 cm x 5 cm grid (Fig.5.2). As it was explained above, this green roof has three different planting mixtures and plants were put into groups and then randomly planted within each mixture areas. Therefore, it was considered that choosing the areas of different combinations of plant species diversity and planting density represented the different types of green roofs. From the author's observation, the quadrats were set up by plant species diversity (High: approximately 6 different species and Low: two or three different species), planting density (High: more than 50 % in total coverage and Low: less than 30 % in total coverage) in January 2006. The bigger difference was preferable for both of planting species diversity (high and low) and planting density (high and low), however, it was very difficult to find for the area of low planting diversity and low density because the overall planting density was about 20 plants / m^2 and the plants were randomly arranged within the group of mixture. Therefore, the above figures were chosen. There were four combinations of plant species diversity and planting density, (1) low plant species diversity and low planting density, (2) low plant species diversity and high planting density, (3) high plant species diversity and low planting density, (4) high plant species diversity and high planting density. These four combinations were chosen in the areas with and without mulch. Each aspect (NE, NW, SE, SW,) has these eight combinations, therefore, 32 quadrates were chosen. The positions of quadrats are shown in Fig.5.1 (attached at the end of this chapter). When the positions of quadrats were set up, several positions were tried and the positions of quadrats which fulfil above criteria were chosen from them. Overall, the quadrats were set up to capture the most of variety of species which were planted on the roof. However, some of species were not prominent at the time of set up (January) and for some species, only small number was used. Therefore, it was impossible to cover all planted species. The recorded parameters were: (1) Percentage of coverage (2) Height (Height of leaves, and when they had flowers, height of flowers, from April to November) (3) Number of self-seeding and weeds invasion (5) Bare ground (July and October). Also, each picture of quadrat from the above was taken. The coverage of creeping plants was measured at the same position with the quadrat (Fig.5.2). In higher plants, coverage was measured at the top of plants (Fig.5.3).



Figs. 5.2 and 5.3. Examples of quadrat (Left: creeping plants, Right: higher plants)

2.4 Statistical analysis

Analysis of Variance (Minitab Release 14) was used to detect the effects of different plant species diversity and planting density, with and without mulch and different aspects. When there were significant differences, means were separated by a Tukey test. To investigate the relationship between bare gournd and total number of weeds per quadrat and the relationship between total plant coverage and total number of weeds, Analysis of Variance as well as regression were calculated (Minitab Release 14).

3. Results

3.1 Seasonal interest

The change over time for the four aspects is shown in Tables 5.1-5.4 (attached at the end of this chapter). Visual interest was found in each season over a year. In the winter (November-March), a few flowers were observed, however, there were some interest such as seed-heads of *A. schoenoprasum, C. scabiosa, S. striatum* and *S. telephium* 'Matrona', plant skeletons *of S. tenuissima*, evergreen foliage of *Sedum* spp. and *S. striatum*. In April, new shoots started to grow. The early flowering species of *P. veris* and bulbs flowered and low growing species were still visible. In May, more species started to flower and buds of *A. schoenoprasum* and flowers of *E. cyparissias* 'Fens Ruby' were eye catching. In June, many species flowered and it was the most colourful month in the year. In July, many species reached their maximum growth. In the late summer to the autumn (August-October), late flowering species such as *S.* 'Herbstfreude', *S. telephium* 'Matrona' and *A. amellus* provided the colours.

3.2. Plant growth and flower performance

3.2.1 Effect of aspect

The effect of aspect on plant growth and flower performance is shown in Table 5.5 (overall plants) and Table 5.6 (individual plants).

For overall mean plant growth, there was no significant difference between aspects. Also, most of the individual species showed no significant difference between aspects. However, there was a tendency that plants showed better growth in the NE and the SE. For six species *F. amethystina, F. glauca, G. lucidum, S. x sylvestris* 'Blauhügel' *S. spathulifolium* var. *purpureum*, there was significant difference between aspect in either mean height or mean diameter. *F. amethystina, F. glauca, G. lucidum a* showed the better growth in the north whereas *S. x sylvestris* 'Blauhügel' and *S. spathulifolium* 'var. *purpureum* showed the better growth in the east and south, respectively.

The mean height and diameter of individual species are compared with those of the typical height and diameter when under cultivation, as stated in the RHS A-Z Encyclopaedia of Garden Plants (Brickell, 2003) (Table 5.7). It was shown that the height and spread of most of species on the roof were close to those of typical mature plants, although the plants grown on the roof tend to be small, especially in diameter. Some species such as *A. juniperifolia, C. scabiosa, G. endressii* 'Wargrave Pink', *L. angustifolia* 'Hidcote', *P. douglasii, S. arachnoideum and V. phoeniceum* were smaller than typical plants. On the contrary, small number of species showed better growth on the roof compare to typical growth on the ground. *K.* 'Border Ballet' (Height) and *P. saxifraga* showed the better growth than typical plants.

The effect of aspect on flowering performance was not very clear. Overall, in the NE, the highest mean flower shoot number was observed whereas the flowering term was shortest. The longest mean flower term was shown in the NW. In the SE, the overall mean flower shoot number was not as high as the north directions, however, it was observed that many species started to flower from the SE and some long flowering species such as *C. rotundifolia* and *G. cinereum* 'Ballerina' flowered over the winter only in the SE. This tendency is clearly observed in Quadrat study which will be introduced in later in this chapter (Quadrat 25, 29, 31). *A. schoenoprasum* and *C. rotundifolia* were significantly affected by the aspect in flowering term, however they showed a different pattern. In *A. schoenoprasum,* the flower shoot number was significantly higher in the east, whereas *C. rotundifolia* showed significantly higher in the west. In flowering term, there was significant difference in three species. Two *Sedum* spp. (*S. sexangulare* and *S. telephium* 'Matrona') had a long flowering season in the south and the east. However, *A. maritima* 'Splendens' showed a longer flowering season in the west, and they showed the shortest flowering season in the NE.

Table 5.5 The effect of aspect on the growth and flower performance of overall plants

Mean plant height (cm)				Mean diameter (cm)				Mean flower shoot number				Flowering term (week)			
NE	NW	SE	SW	NE	NW	SE	SW	NE	NW	SE	SW	NE	NW	SE	SW
39.77 a	37.52 a	38.68 a	37.51 a	34.16 a	32.45 a	34.04 a	31.61 a	41.55 a	40.92 a	39.33 a	40.82 a	6.47 a	6.69 a	6.59 a	6.50 a
ns SE=±2.55				ns SE=±1.44				ns SE=±5.74				ns SE=±0.40			

SE=Standard Error, Letters of Tukey multiple comparison are compareing values within a row in each parameter. Means with the same letter do not differ significantly from each other.

Table 5.6 The effect of aspect on the growth and flower performance of individual plants

	Mean height (cm)				Mean diameter (cm)				Mean flower shoot number				Flowenng term (week)			
	NE	NW	SE	SW	NE	NW	SE	SW	NE	NW	SE	SW	NE	NW	SE	SW
A. schoenoprasum	56.83 a	41.90 a	52.17 a	52.40 a	33.03 a	25.27 a	35.77 a	25.67 a	43.67 ab	24.33 b	51.33 a	23.00 b	9.33 a	10.00 a	10.00 a	9.33 a
	ns SE=±4 45				ns SE=±3.10				P<0 01 SE=± 4.98				ns SE=± 1 89			
A. juniperifolia	3.00 a	2.97 a	2.87 a	4.00 a	7.10 a	7.57 a	7.68 a	7.58 a	7.00 a	10.00 a	12.67 a	10.33 a	3.33 a	4.00 a	4.00 a	4.00 a
	Ns SE=±0.30				ns SE=±0.55				ns SE=±4.59				ns SE=±0.33			
A. maritima 'Splendens'	26.13 a	31.73 a	29.93 a	30.90 a	14.10 a	19.28 a	16.67 a	18.10 a	13.33 a	25.33 a	18.33 a	15.33 a	5.33 b	16.67 a	8.00 a	12.67 a
	ns SE=± 4.77				ns SE=± 1.61				ns SE=± 5.38				P<0.05 SE=± 2.16			
A. amellus	67.80 a	60.60 a	56.83 a	57.57 a	41.05 a	40.23 a	36.83 a	38.00 a	9.67 a	11.00 a	10.67 a	10.67 a	12.67 a	12.00 a	10.00 a	10.00 a
	ns SE=± 6.27				ns SE=± 6 04				ns SE=± 2 27				ns SE=± 0 88			
C. nepeta	50.80 a	58.57 a	55.90 a	47.90 a	47.47 a	52.32 a	47.88 a	42.18 a	33.67 a	63.33 a	52.33 a	54.00 a	13.33 a	14.00 a	9.33 a	13.33 a
	ns SE=± 6 28				ns SE=± 7.59				ns SE=± 14 40				ns SE=± 2.16			
C. rotundifolia	27.77 a	30.67 a	40.93 a	36.07 a	10.78 a	14.22 a	12.17 a	12.58 a	7.67 b	24.33 a	17.67 a	23.00 a	9.33 a	12.67 a	11.33 a	9.33 a
	ns SE=±3 66				ns SE=±1 68				P<0 01 SE=±1.89				ns SE=±3.38			
C. scabiosa	92.07 a	88.17 a	87.10 a	94.17 a	56.05 a	47.70 a	51.77 a	40.23 a	13.33 a	9.00 a	13.33 a	10.00 a	4.67 a	3.33 a	4.00 a	2.67 a
	ns SE=±9.10				ns SE=±7 97				ns SE=±3 965				ns SE=±0.58			
D. deltoides	18.33 a	22.33 a	22.03 a	17.67 a	19.25 a	24.67 a	25.02 a	17.92 a	27.00 a	77.33 a	68.33 a	68.33 a	6.00 a	5.33 a	5.33 a	4.67 a
	ns SE=±1.72				ns SE=±2.09				ns SE=±13 52				ns SE=±0.58			
E. ciliatum	9.90 a	9.77 a	9.57 a	11.17 a	27.47 a	25.60 a	34.55 a	25.98 a	15.00 a	14.67 a	31.00 a	12.33 a	22.00 a	20.67 a	24.00 a	21.33 a
	ns SE=±1 38				ns SE=±5 22				ns SE=±11.52				ns SE=±1.11			
E. manescavii	38.00 a	33.10 a	38.00 a	40.90 a	37.23 a	35.58 a	45.92 a	49.38 a	10.67 a	11.67 a	16.33 a	13.33 a	12.67 a	12.00 a	16.00 a	14.67 a
	ns SE=±4 54				ns SE=±4 48				ns SE=±3.19				ns SE=±2 21			
E. cyparissias 'Fens Ruby'	31.17 a	28.97 a	28.50 a	29.83 a	44.82 a	38.58 a	37.83 a	36.00 a	33.00 a	19.00 a	24.33 a	23.00 a	6	6	6	6
	ns SE=±2.16				ns SE=±2 81				ns SE=±6.33				-			
F. amethystina	78 90	70 03	78 30	71.40	30 22	40.07	34 47	25.78	174.7	130.3	105.0	114 3	4	4	4	4

	a	a	a	a	ab	a	ab	b	a	a	a	a				
	ns SE=±3 32				P<0 05 SE=±2.86				ns SE=±33 76				-			
F. glauca	87.00 a	69.00 b	69.10 b	71.33 b	54.93 a	46.45 a	41.63 a	41.42 a	100.3 a	174.7 a	116.0 a	138.7 a	4	4	4	4
	P<0.05 SE=±3 24				ns SE=±5.57				ns SE=±43 87				-			
G. verum	60.83 a	62.10 a	65.30 a	60.53 a	65.32 a	67.50 a	63.60 a	62.63 a	71.33 a	57.00 a	48.67 a	58.33 a	8.00 a	9.33 a	7.33 a	8.67 a
	ns SE=±7 60				ns SE=±7 83				ns SE=±15 96				ns SE=±1.92			
G. cinereum 'Ballerina'	19.13 a	19.50 a	19.77 a	23.57 a	19.33 a	13.33 a	14.67 a	14.67 a	2.67 a	5.67 a	2.67 a	1.67 a	8.67 a	12.67 a	13.33 a	8.67 a
	ns SE=±2.43				ns SE=±5.12				ns SE=±1.01				ns SE=±2.60			
G. endressii 'Wargrave Pink'	16.67 a	12.50 a	21.77 a	13.33 a	27.00 a	21.18 a	18.72 a	27.92 a	8.33 a	5.33 a	8.00 a	5.00 a	7.33 a	6.00 a	7.33 a	7.33 a
	ns SE=±4.88				ns SE=±4.37				ns SE=±2 93				ns SE=±1.29			
G. lucidum	16.43 a	12.57 ab	14.77 a	3.33 b	20.85 a	19.20 a	20.03 a	17.37 a	4.67 a	4.67 a	3.00 a	2.00 a	5.33 a	5.33 a	5.33 a	5.33 a
	P<0.05 SE=±2.27				ns SE=±3.13				ns SE=±1.21				ns SE=±0.67			
G.repens 'Dorothy Teacher'	7.83 a	9.47 a	7.57 a	9.43 a	19.50 a	22.23 a	19.93 a	20.73 a	18.67 a	43.33 a	8.33 a	25.33 a	8.00 a	14.00 a	8.67 a	12.00 a
	ns SE=±2.48				ns SE=±2.81				ns SE=±9 01				ns SE=±1.94			
H. nummularium Wisley Primrose'	15.07 a	15.40 a	16.00 a	12.80 a	28.98 a	20.78 a	25.38 a	18.37 a	11.33 a	13.67 a	12.00 a	10.33 a	3.33 a	3.33 a	4.00 a	3.33 a
	ns SE=±2 91				ns SE=±3 95				ns SE=± 2.77				ns SE=±0.58			
H. sempervirens	130.8 a	127.8 a	137.0 a	138.0 a	48.32 a	56.58 a	55.98 a	60.18 a	33.00 a	36.33 a	38.67 a	39.67 a	4	4	4	4
	ns SE=± 3 80				ns SE=±4.24				ns SE=±13 68				-			
K. 'Border ballet'	114.8 a	115.4 a	111.1 a	102.4 a	67.38 a	61.73 a	60.52 a	59.68 a	2.67 a	3.00 a	2.33 a	2.67 a	5.33 a	6.00 a	4.67 a	4.67 a
	ns SE=±11.80				ns SE=±5.28				ns SE=±0.58				ns SE=±0 82			
L. angustifolia 'Hidcote'	26.90 a	23.27 a	26.63 a	21.53 a	17.62 a	17.87 a	20.72 a	19.53 a	12.67 a	6.00 a	10.00 a	12.67 a	6.00 a	4.67 a	5.33 a	4.67 a
	ns SE=±2.35				ns SE=±2.59				ns SE=±5 65				ns SE=±0.58			
L. x Superbum	64.27 a	55.13 a	65.07 a	50.07 a	35.45 a	32.50 a	39.92 a	42.05 a	27.33 a	16.33 a	27.67 a	33.00 a	6.00 a	4.67 a	5.33 a	4.67 a
	ns SE=±4 68				ns SE=±4.11				ns SE=±6.10				ns SE=±0.58			
L. latifolium	58.63 a	58.63 a	57.57 a	54.00 a	36.30 a	43.63 a	53.40 a	36.40 a	6.33 a	6.00 a	4.33 a	4.33 a	8.67 a	6.67 a	7.33 a	8.00 a
	ns SE=±6.32				ns SE=±6 66				ns SE=±1.12				ns SE=±1.00			
M. ciliata	70.10 a	70.10 a	65.10 a	74.83 a	33.47 a	29.78 a	35.28 a	27.12 a	81.00 a	51.67 a	92.00 a	62.00 a	5.33 a	4.67 a	6.67 a	6.00 a
	ns SE=±3 66				ns SE=±4.48				ns SE=±9.32				ns SE=±1.16			
N. x faassenii	30.13 a	33.40 a	34.13 a	30.60 a	45.37 a	43.75 a	46.35 a	46.50 a	3.33 a	10.00 a	10.33 a	20.00 a	12.00 a	10.00 a	12.00 a	10.67 a
	ns SE=±3.08				ns SE=±5.47				ns SE=±6.14				ns SE=±1.94			
O. vulgare 'Herrenhausen'	43.43 a	44.53 a	42.23 a	46.60 a	57.60 a	48.33 a	54.97 a	55.67 a	45.67 a	32.67 a	20.67 a	38.33 a	10.00 a	10.00 a	11.33 a	11.33 a
	ns SE=±3.19				ns SE=±4.70				ns SE=±6.13				ns SE=±0.47			
P. saxifraga	33.30 a	37.47 a	36.80 a	37.23 a	57.30 a	71.50 a	53.30 a	56.57 a	261.3 a	369.7 a	290.0 a	221.0 a	16.67 a	16.67 a	18.00 a	17.33 a
	ns SE=±3 88				ns SE=±8.19				ns SE=±76.62				ns SE=±0.82			
P. douglasii	3.50 a	5.90 a	4.33 a	4.00 a	13.97 a	16.28 a	13.58 a	15.32 a	22.00 a	24.33 a	4.33 a	58.00 a	2.00 a	2.00 a	1.33 a	2.00 a
	ns SE=±0 81				ns SE=±1.65				ns SE=±25.71				ns SE=±0.33			
P. veris	25.80 a	24.67 a	26.67 a	22.40 a	18.60 a	20.60 a	19.62 a	22.07 a	10.00 a	11.33 a	13.00 a	11.33 a	11.33 a	11.33 a	12.67 a	10.67 a
	ns SE=±3.55				ns SE=±1.88				ns SE=±2.67				ns SE=±2.11			
P. vulgaris	35.53 a	30.27 a	24.90 a	30.27 a	26.57 a	19.05 a	26.17 a	23.35 a	2.33 a	2.33 A	2.33 a	2.33 a	2.67 a	2.67 a	4.00 a	3.33 a
	ns SE=±4.22				ns SE=±4.14				ns SE=±0.60				ns SE=±0.58			
S. x sylvestris 'Blauhügel'	55.77 a	40.17 b	54.17 a	44.97 ab	30.68 a	29.80 a	38.53 a	26.37 a	14.33 a	16.67 a	18.67 a	10.67 a	12.67 a	7.33 a	9.33 a	13.33 a
	P<0.05 SE=±2.83				ns SE=±4.60				ns SE=±3.55				ns SE=±1.86			
S. acre 'Golden Queen'	6.17 a	6.67 a	3.77 a	2.17 a	17.83 a	19.30 a	19.13 a	14.17 a	46.00 a	66.00 a	54.00 a	23.67 a	2.67 a	2.00 a	2.67 a	2.67 a
	ns SE=±0.51				ns SE=±1.93				ns SE=±13 29				ns SE=±0.58			
S. album 'Coral carpet'	8.67 a	9.90 a	8.50 a	9.07 a	21.62 a	21.27 a	21.98 a	14.03 a	49.00 a	55.67 a	47.67 a	13.67 a	4.67 a	3.33 a	2.67 a	2.00 a
	ns SE=±0.76				ns SE=±1.94				ns SE=±22.64				ns SE=±0 58			
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'	16.00 a	13.33 a	14.50 a	12.43 a	49.33 a	40.17 a	38.53 a	36.60 a	65.67 a	20.00 a	8.00 a	20.67 a	17.33 a	18.00 a	14.67 a	13.33 a
	ns SE=±2.12				ns SE=±6.58				ns SE=±16 93				ns SE=±1.73			
S. 'Herbstfreude'	48.73 a	44.73 a	50.53 a	48.17 a	52.90 a	43.52 a	49.92 a	46.40 a	27.00 a	10.67 a	19.33 a	17.33 a	2.00 a	4.00 a	4.67 a	2.67 a
	ns SE=±3 23				ns SE=±3 85				ns SE=±4.24				ns SE=±0 94			
S. hispanicum 'Silver Carpet'	4.30 a	4.27 a	2.27 a	6.07 a	15.63 a	12.37 a	19.53 a	17.37 a	110.00 a	91.67 a	16.00 a	257.33 a	6.00 a	5.33 a	2.67 a	8.00 a
	ns SE=±0 83				ns SE=±1 99				ns SE=±58 84				ns SE=±1 25			
S. reflexum	29.50 a	30.87 a	25.33 a	23.70 a	31.07 a	26.57 a	27.02 a	25.72 a	12.33 a	10.00 a	13.67 a	8.33 a	2	2	2	2
	ns SE=±2 67				ns SE=±3.99				ns SE=±4 82				-			
S. sexangulare	8.27 a	9.27 a	9.90 a	9.70 a	26.33 a	21.23 a	27.30 a	20.80 a	151.67 a	79.33 a	200.67 a	103.00 a	6.00 ab	5.33 b	7.33 ab	8.00 a
	ns SE=±1.00				ns SE=±3.41				ns SE=±57.57				P<0.05 SE=±0 47			
S. spathulifolium 'Cape Blanco'	1.93 b	1.70 b	1.97 b	3.00 a	13.57 a	13.13 a	13.50 a	14.25 a	No Flower				No Flower			
	P<0.01 SE=±0.13				ns SE=±0.93											
S. spurium 'Green Mantle'	13.70 a	13.43 a	6.63 a	16.31 a	25.73 a	28.87 a	37.83 a	28.50 a	3.67 a	5.00 a	2.67 a	21.67 a	2.00 a	2.67 a	0.67 a	2.67 a
	ns SE=±4 36				ns SE=±6.14				ns SE=±4 92				ns SE=±0 58			
S. telephium 'Matrona'	53.00 a	56.00 a	51.33 a	51.40 a	52.67 a	51.00 a	49.80 a	34.00 a	23.00 a	16.67 a	17.00 a	9.33 a	8.00 ab	7.33 ab	9.33 a	6.00 b
	ns SE=±4 56				ns SE=±11.17				ns SE=±6.13				P<0.01 SE=±0.47			

S. arachnoideum	0.33 a	0.47 a	0.80 a	0.73 a	5.52 a	7.62 a	4.72 a	5.13 a	No Flower				No Flower			
	ns SE=±0 25				ns SE=±0.81											
S. uniflora	17.90 a	16.33 a	20.83 a	15.80 a	43.30 a	46.20 a	64.37 a	40.80 a	49.67 a	118.00 a	143.33 a	37.00 a	14.67 a	16.67 a	19.33 a	13.33 a
	ns SE=±1 55				ns SE=±6 68				ns SE=±42.38				ns SE=±1.94			
S. striatum	76.77 a	74.83 a	77.13 a	68.87 a	53.88 a	49.38 a	56.17 a	55.58 a	19.33 a	12.67 a	26.00 a	22.33 a	6.00 a	6.00 a	4.00 a	5.33 ab
	ns SE=±4.45				ns SE=±3 48				ns SE=±6 47				ns SE=±0.33			
S. tenuissima	90.20 a	77.33 a	85.57 a	82.40 a	56.80 a	39.75 a	47.45 a	47.18 a	281.7 a	169.0 a	167.0 a	277.7 a	4	4	4	4
	ns SE=±4 84				ns SE=±5 26				ns SE=±84.34				-			
S. byzantina 'Silver Carpet'	67.77 a	55.57 a	60.00 a	63.20 a	72.13 a	45.50 a	46.47 a	61.73 a	25.00 a	6.67 a	26.00 a	10.67 a	6.00 a	4.67 a	4.67 a	5.33 a
	ns SE=±7.62				ns SE=±9 86				ns SE=±7.49				ns SE=±0.58			
V. phoeniceum	58.07 a	56.30 a	69.17 a	65.43 a	21.17 a	20.77 a	19.27 a	25.13 a	2.00 a	3.00 a	1.67 a	1.33 a	2.67 a	3.33 a	4.00 a	4.00 a
	ns SE=±8.35				ns SE=±3 00				ns SE=±0 37				ns SE=±0 47			

P=Probability, SE=Standard Error, Letters of Tukey multiple comparison are compareing values within a row in each parameter. Means with the same letter do not differ significantly from each other.

Table 5.7 Comparison with typical plants

	Roof		RHS dictionary	
	Height (cm)	Diameter (cm)	Height (cm)	Diameter (cm)
A. schoenoprasum	50.8	29.9	30-60	5
A. juniperifolia	3.2	7.5	5-8	15
A. maritima 'Splendens'	29.7	17.0	(20)	(30)
A. amellus	60.7	39.0	30-60	45
C. nepeta	53.3	47.5	to 45	50-75
C. rotundifolia	33.9	12.4	12-30	12-30
C. scabiosa	90.4	48.9	150	90
D. deltoids	20.1	21.7	20	30 or more
E. ciliatum	10.1	28.4	20-40	20-40
E. manescavii	37.5	42.0	-	-
E. cyparissias 'Fens Ruby'	29.6	39.3	(20-40)	(indefinite)
F. amethystina	74.7	32.6	50	to 45
F. glauca	74.1	46.1	to 30	25
G. verum	62.2	64.8	-	-
G. cinereum 'Ballerina'	20.5	22.9	15	30
G. endressii 'Wargrave Pink'	34.8	23.7	60	90
G. lucidum	11.8	19.4	-	-
G. repens 'Dorothy Teacher'	8.6	20.6	5	40
H. nummularium 'Wisley Primrose'	14.8	23.4	(15)	(20)
H. sempervirens	133.4	55.3	140	60
K. 'Border Ballet'	110.9	62.3	60	60
L. angustifolia 'Hidcote'	24.6	18.9	60	75
L. x superbum	58.6	37.5	90	60
L. latifolium	57.2	42.4	60 or more	45
M. ciliata	35.0	70.0	-	-
N. x faassenii	32.1	45.5	to 45	to 45
O. laevigatum 'Herrenhausen'	44.2	54.1	45	45
P. saxifraga	36.2	59.7	10	20
P. douglasii	4.4	14.8	20	30
P. veris	24.9	20.2	25	25
P. vulgaris	30.2	23.8	10-20	20
S. x sylvestris 'Blauhügel'	48.8	31.3	50	45
S. acre 'Golden Queen'	5.5	17.6	(5)	(60)
S. album 'Coral Carpet'	9.0	19.7	-	-
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'	14.1	41.2	-	-
S. 'Herbstfreude'	48.0	48.2	60	60
S. hispanicum 'Silver Carpet'	4.2	16.2	-	-
S. reflexum	27.4	27.6	10	60
S. sexangulare	9.3	23.9	-	-
S. spathulifolium var. *purpureum*	2.2	13.6	(10)	(60)
S. spurium 'Green Mantle'	12.5	30.2	(10)	(60)
S. telephium 'Matrona'	52.9	46.9	(60)	(30)
S. arachnoideum	0.6	5.7	8	30
S. uniflora	17.7	48.7	(15)	(20)
S. striatum	74.4	53.8	90	25
S. byzantina 'Silver Carpet'	61.6	56.5	45	60

S. tenuissima	63.1	83.9	60	30
V. phoeniceum	62.2	21.6	120	45

The figures in ( ) indicates same species but not indicate this subspecies

3.2.2 Flowering performance

Change of number of flowering species over time is shown in Fig 5.4. No month was observed without flowering from February to November 2006 and at least 3 species flowered in each month. From April, the number of flowering species increased and at the end of June, the highest number of flowering species was shown. June and July were the most colourful months. After July, the number decreased, however, in the autumn (August and September), it increased slightly again and decreased significantly after September.

The total flowering period of individual species on the green roof and their characteristics are shown in Table 5.8 and Table 5.9 (Table 5.9 is attached at the end of thesis) respectively. If more than one of each of the twelve representative plants flowered of each species, this was counted as a flowering period.

A. maritima 'Splendens', *G. cinereum* 'Ballerina', *S.uniflora, E. ciliatum, A. schoenoprasum, C. rotundifolia, E. manescavii, C. nepeta* and *S. kamtschaticum* var. *floriferum* 'Weihenstephaner Gold' showed a very long flowering performance and their total flowering periods were over 5 months. Especially, *S. uniflora, E. ciliatum, S. kamtschaticum* var. *floriferum* 'Weihenstephaner Gold' and *C. nepeta* had a high percentage of number of flowering plants for a long term. On the contrary, in *A. maritima* 'Splendens' and *G. cinereum* 'Ballerina', a small percentage of number of flowering was observed over a long time. For example, only one plant had flower for three months in *G. cinereum* 'Ballerina'. It is interesting to note that *A. schoenoprasum, A. maritima* 'Splendens', *G. verum, G. cinereum* 'Ballerina', *M. ciliata* and *N. x faassenii* flowered again in the autumn after they finished flowering completely in the spring. Overall, the long flowering species showed the low visual quality at the beginning and then gradually they increase their visual quality and decreased again.

Bulb species, grass species and Sedum species had a short flowering period (less than one month) although there were some exceptions such as *S. kamtschaticum* var. *floriferum* 'Weihenstephaner Gold'. Particularly, *A. karataviense, A. caeruleum, C. tommasinianus* 'Whitewell Purple', *P. douglasii, S. reflexum, S. arachnoideum, T. praestans* 'Fusilier' and *S. spathulifolium* var. *purpureum* showed short flowering and they flowered for less than two weeks. These species have the tendency to produce a small number of flowers and/or they started and finished flowering at the nearly same time. Also, generally, short flowering specie showed the best visual quality at the beginning. However, some species, such as *C. tommasinianus* 'Whitewell Purple' and *S. arachnoideum* did not show the good visual quality throughout their short time of flowering.

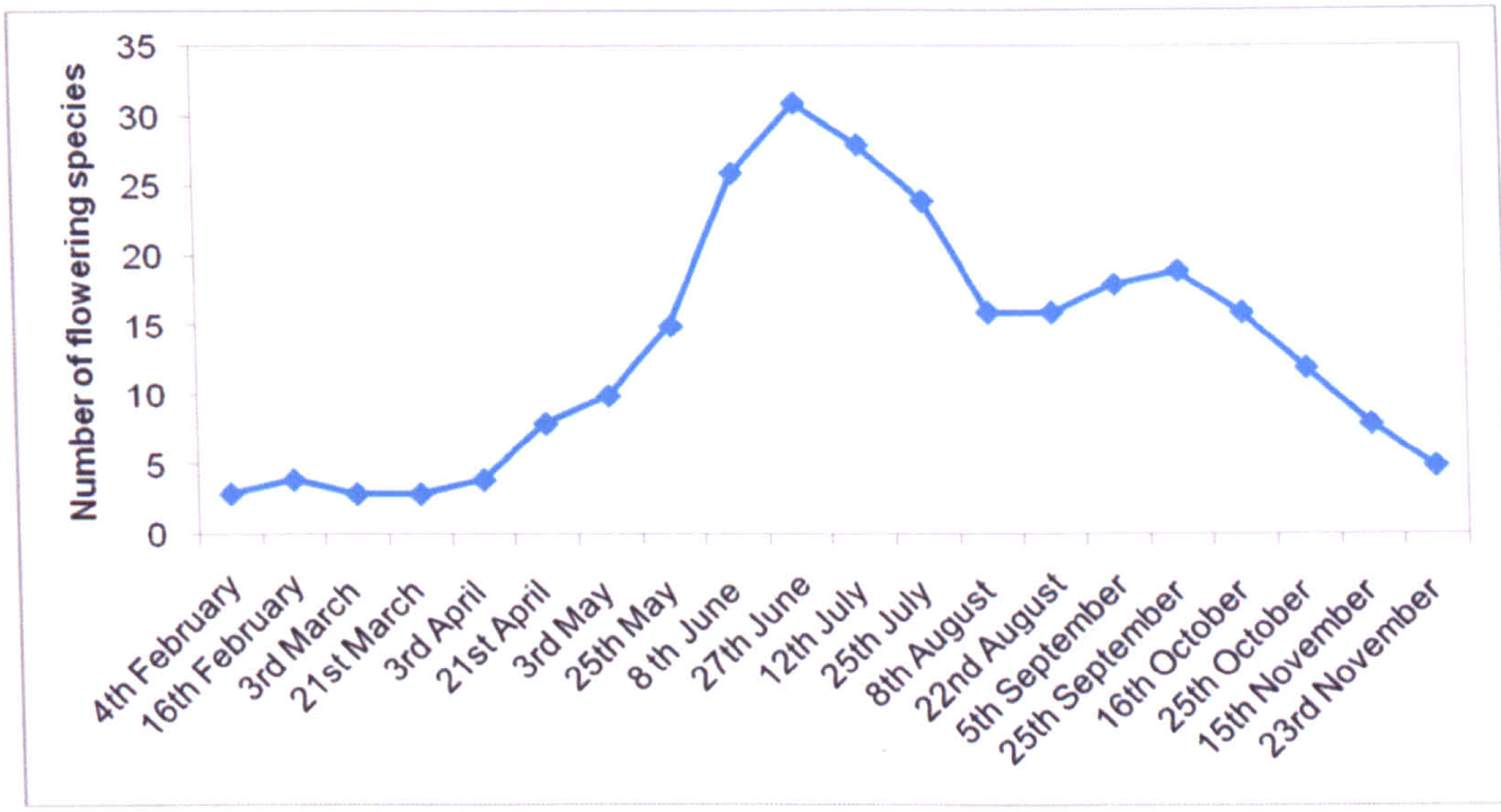


Fig. 5.4 Change of number of flowering species over time

Table 5.8 Total flowering period of each species on the green roof (months)

Very long period (5-7.5 months)		Long period (3-4.5 months)		Medium period (1.5-2.5 months)		Short period (0-1month)	
A. maritima 'Splendens'	7.5	*P. saxifraga*	4.5	*L. latifolium*	2.5	*A. juniperifolia*	1
G.cinereum 'Ballerina'	7.5	*G. verum*	4	*M. ciliata*	2.5	*F. amethystina*	1
S.uniflora	6.5	*G. repens* 'Dorothy Teacher'	4	*S. telephium* 'Matrona'	2.5	*F. glauca*	1
E. ciliatum	6.5	*N. x faassenii*	4	*K.* 'Border Ballet'	2	*H. sempervirens*	1
A. schoenoprasum	6	*P. veris*	4	*S. hispanicum* 'Silver Cover'	2	*M. armeniacum*	1
C. rotundifolia	6	*S. x sylvestris* 'Blauhügel'	4	*S. sexangulare*	2	*P. vulgaris*	1
E. manescavii	6	*A. amellus*	3.5	*C. scabiosa*	1.5	*S. acre* 'Golden Queen'	1
C. nepeta	5	*G. endressii* 'Wargrave Pink'	3.5	*D. deltoides*	1.5	*S. spurium* ' Green Mantle'	1
S. kamtschaticum var. *floriferum* 'Weihenstephaner gold'	5	*O. laevigatum* 'Herrenhausen'	3	*E. cyparissias* 'Fens Ruby'	1.5	*S. tenuissima*	1
				G. lucidum	1.5	*T. tarda*	1
				H. nummularium 'Wisley primrose'	1.5	*A. karataviense*	0.5
				L. angustifolia 'Hidcote'	1.5	*A. caeruleum*	0.5
				L. x superbum	1.5	*C. tommasinianus* 'Whitewell Purple'	0.5
				S. album 'Coral Carpet'	1.5	*P. douglasii*	0.5
				S. 'Herbstfreude'	1.5	*S. reflexum*	0.5
				S. striatum	1.5	*S. arachnoideum*	0.5
				S. byzantina 'Silver Carpet'	1.5	*T. praestans* 'Fusilier'	0.5
						S. spathulifolium var. *purpureum*	0

3.3 Quadrat study 1 (plant growth, flowering succession and dynamic change)

The results of the 32 quadrats are summarised in Chart 1 to 32 (attached at the end of thesis). These charts were produced by Gracia-Albarad (2005) and they were adapted for this study. The charts consist of (1) The set of ten pictures that were taken from the same vegetation unit (quadrat) in each month from February to November. (2) Flower succession (3) Change of coverage of individual species over time (4) Change of height of individual species over time. From these, (1) growth characteristics of individual plant species and (2) the effect of plant species diversity and planting density on change of plant growth were investigated.

3.3.1. The growth characteristics of individual plant species over time

From the above results of quadrats, the growth characteristics of individual plant species over time was analyzed in three sections, coverage, vertical and the best growing season. In coverage and vertical, two categories were used, growth type (maximum size) and growth pattern (phenology). Three growth types were identified, small, medium and large (high): coverage (Small = coverage of plants < 30 %, Medium = 30 % ≤coverage of plants < 60 %, Large = coverage of plants ≥60 %) and vertical (Low = plant height < 20 cm, Medium = 20 cm ≤plant height < 50 cm, High = plant height ≥50 cm). The growth patterns were also divided into three types (Stable = their coverage or height do not change much over time, Bell Shape = their coverage or height increases and reaches a maximum in a certain time and then declines, Increase = their coverage or height increase and they are stable after they reach maximum growth). It is important to examine season of the best performance of individual species and length of flowering term to maximize the aesthetic of green roofs. Therefore, the best growing season and the best flowering season were classified in three (Early = from February to May, Medium = from June to August, Late = from September to November) Individual plant growth could be divided into 6 patterns using these categories. The classification of individual plant growth patterns and number of species for each pattern is shown in Table 5.9. The result of growth patterns of individual plant species is shown in Table 5.10. As well as above classification, the flowering lengths (Short = 0, flowering ≤1 month, Medium = flowering for 2-3 months, and Long = flowering for at least 4 months) are added in Table 5.10.

In Pattern 1 and Pattern 2, growth tended to be slow and coverage did not change much over time. The difference between Patten 1 and Patten 2 was the structure of flowering stem. Plants which had flowers just above leaves were classified in Pattern 1 (Height change over time is also stable) whereas the plants with higher flower stems were in Pattern 2 (Height change over time is bell shape). The species in these two patterns tend to have short heights and they were not very prominent in the summer, although most of them provided attractive foliage in the winter. In Patten 1, low growing *Sedum* spp. such as *S. acre* 'Golden Queen' and and in Pattern 2, *C. rotundifolia* and *D. deltoides* were included. Semi-evergreen species were classified in Pattern 3 and Pattern 4. They started to grow in the spring, showed maximum growth in the summer and the coverage decreased in the autumn and in the winter, most of leaves died down. The species which have separate flower stems such as *E. manescavii*, *F. glauca* and *L. latifolium* were classified in Patten 3 whereas the species which have flowers on the top of the stems such as *A. schoenoprasum*, *O. laevigatum* 'Herrenhausen', *S. x sylvestris* 'Herrenhausen' and *S. telephium* 'Matrona' were classified in Patten 4. In Pattern 5 and Pattern 6, they showed the vigorous growth throughout a year and their coverage and height increased and kept stable. The difference between Pattern 5 and Pattern 6 was the structure of flower stems. *H. sempervirens* and *S. uniflora* belong to pattern 5 and *C. nepeta* and *P. saxifraga* belong to pattern 6. In this study, a high number of species was classified in Pattern 1 and Pattern 3.

For the best growing season, smaller plants (Pattern 1, 2 and 3) showed their best in early to medium, whereas larger plants (Pattern 4, 5 and 6) showed their best in medium to late. The largest number of species showed the best growth in middle season, following by late season and early season. Therefore, the species of the early growing season (e.g. *P. veris, M. armeniacum*) and the species of late growing season (e.g. *C. nepeta, E. ciliatum, N.* x *faassenii, S. telephium* 'Matrona') would be particularly valuable.

Table 5.9 The classification of individual plant growth patterns and number of species which are belong to their pattern

	Coverage		Vertical		Best growing Season	Number of species
	Growth type	Growth pattern	Growth type	Growth pattern		
Pattern 1	Small	Stable	Low	Stable	Early-Medium	14
Pattern 2	Small	Stable	Low-Medium	Bell	Early-Medium	6
Pattern 3	Small-Large	Bell	Low-Tall	Bell	Early-Medium	11
Pattern 4	Medium	Bell	Medium-Tall	Increase	Medium-Late	4
Pattern 5	Medium-Large	Increase	Low-Tall	Bell	Medium-Late	5
Pattern 6	Medium-Large	Increase	Medium-Tall	Increase	Medium-Late	3

Coverage type (Small=Plants <30%, Medium=30% ≤Plants<60%, Large=Plants ≥60%)
Vertical type (Low=0<Plants<20cm, Medium=20cm ≤Plants<50cm, High=Plants ≥50cm)
Coverage and vertical growth pattern (Stable=their coverage or height do not change much over time, Bell Shape= their coverage or height increases and reaches a maximum in a certain time and then declines, Increase= their coverage or height increase and they are stable after they reach maximum growth).

Best growing season (Early= from February to May, Medium=from June to August, Late= from September to November)

Table 5.10 The growth pattern of individual plant species

	Coverage		Vertical		Season			Growth Pattern	Quadrat number
Species	Growth type	Growth pattern	Growth type	Growth pattern	Growing season	Flower season	Flower term		
A. schoenoprasum	Medium	Increase	Medium	Increase	Medium and Late	Early to Late	Short to Long	5	6, 25, 26,31
A .juniperifolia	Small	Stable	Low	Stable	Early – Medium	Early	Short	1	1,5,9,13, 17,21,22, 29,30
A. caeruleum	Small	Bell	Medium	Bell	Medium	Medium	Short	3	2,10,14,1 8
A. amellus	Medium	Stable	Tall	Bell	Medium-Late	Medium	Short	2	32
C. nepeta	Medium	Increase	Tall	Increase	Medium-Late	Medium-Late	Medium	6	16,22,24
C. rotundifolia	Small	Stable	Low (Medium in flower)	Bell	Medium	Medium-Late	Medium to Long	2	21,23,27, 29
C. scabiosa	Medium	Bell	Medium	Bell	Medium	Medium	Shot	3	18,26, 28
D. deltoides	Small	Stable	Low	Bell	Medium	Medium	Short	2	13,14,16, 22,23, 29, 30,32
E. ciliatum	Small	Stable	Low	Stable	Late	Medium-Late	Long	1	5,7,15
E. manescavii	Small	Bell	Medium	Bell	Medium	Medium	Medium	3	10,14
F. amethystina	Small	Stable	Medium (Tall in flower)	Bell	Medium	Medium	Short	2	14,28
F. glauca	Medium	Bell	Medium (High in flower)	Bell	Medium-Late	Medium	Short-Medium	3	4, 12, 32
G. verum	Medium	Bell	Medium	Bell	Medium-Late	Medium	Short	3	16
G. cinereum 'Ballerina'	Small	Stable	Low	Bell	Late	Medium-Late	Long	2	31
G. endressii 'Wargrave Pink'	Medium Small(6,1 4)	Bell	Low (Medium in flower)	Bell	Medium-Late	Medium	Short-Medium	3	2, 6, 8,14
H. nummularium 'Wisley Primrose'	Small	Stable	Low	Stable	Early-Medium,	Medium	Short	1	10,30
H. sempervirens	Medium	Increase	Medium (High in flower)	Bell	Medium-Late	Medium	Short	5	20,24
L. angustifolia 'Hidcote'	Small	Stable	Low	Bell	Medium	Medium	Short	2	6
L. x superbum	Medium -Large	Bell	Medium (Tall in flower)	Increase	Medium	Medium	Short	4	6,8,28
L. latifolium	Medium -Large	Bell	Medium (Tall in flower)	Bell	Medium	Medium	Medium	3	2, 14,16
M. ciliata	Medium	Increase	Tall	Bell	Medium	Medium	Short	5	18
M. armeniacum	Small	Stable	Low	Bell	Early-Medium	Early	Short	2	1,9,13,17 , 25
N. x faassenii	Large	Increase	Medium	Bell	Late	Medium-Late	Medium	5	22, 32
O. laevigatum 'Herrenhausen'	Medium	Bell	Medium	Increase	Medium-Late	Medium-Late	Medium	4	6,8,10,12 ,32
P. saxifraga	Medium	Increase	Medium	Increase	Medium-Late	Medium-Late	Medium-Long	6	4, 13,15, 17,20,22, 23,29,31
P. douglasii	Small	Stable	Low	Stable	Early	Medium	Short	1	1
P. veris	Small	Stable	Low	Stable	Early	Early	Short-Medium	1	2, 4,7,8,9, 16,21,25, 27,29,32

P. vulgaris	Small	Bell	Low	Bell	Medium	-	-	3	9,11
S. x *sylvestris* 'Blauhügel'	Medium	Bell	Medium	Increase	Late	Medium	Medium	4	8,16
S. acre 'Golden Queen'	Small	Stable	Low	Stable	Medium	Medium	Short	1	11,14,15, 17,23, 25
S. album 'Coral carpet'	Small	Stable	Low	Stable	Medium	Medium	Short	1	5,9,27, 31
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'	Small - Medium	Stable	Low	Stable	Medium	Early-Late	Short-Long	1	11,13,16, 29
S. hispanicum 'Silver Carpet'	Small	Stable	Low	Stable	Medium	Medium	Short	1	1,15,27
S. reflexum	Small	Stable	Low	Stable	Medium	Medium	Short	1	5,13,21, 31
S. sexangulare	Small	Stable	Low	Stable	Medium	Medium	Short	1	7,21
S. spathulifolium var. *purpureum*	Small	Stable	Low	Stable	Early-Medium	-	-	1	5
S. spurium 'Green Mantle'	Small	Stable	Low	Stable	Medium-Late	-	-	1	11, 16,1719, 30
S. telephium 'Matrona'	Medium	Bell	Medium	Increase	Medium-Late	Medium-Late	Medium	4	14
S. arachnoideum	Small	Stable	Low	Stable	Medium	-	-	1	7,9,21,27
S. uniflora	Medium-Large	Increase	Low	Bell	Medium-Late	Medium-Late	Long	5	3,5,7,11, 13,19,23
S. striatum	Large	Bell	High	Bell	Medium	Medium	Short	3	3,15,19, 23
S. tenuissima	Large	Increase	High	Increase	Medium	Medium	Short	6	16,22,24,
S. byzantina 'Silver Carpet'	Medium-Large	Increase	Low (Medium-High in flower)	Bell	Medium	Medium	Short-Medium	5	2, 6, 12,26,28
V. phoeniceum	Small	Bell	Low (High in flower)	Bell	Medium	Medium	Short	3	2, 18, 26, 30

Coverage type (Small=Plants <30%, Medium=30% ≤Plants<60%, Large=Plants ≥60%)
Vertical type (Low=0<Plants<20cm, Medium=20cm ≤Plants<50cm, High=Plants ≥50cm)
Coverage and vertical growth pattern (Stable=their coverage or height do not change much over time, Bell Shape= their coverage or height increases and reaches a maximum in a certain time and then declines, Increase= their coverage or height increase and they are stable after they reach maximum growth).
Seasonal (Early= from February to May, Medium=from June to August, Late= from September to November)
Flowering term (Short = 0< flowering ≤1 month, Medium= 2months ≤flowering ≤3months, Long= flowering ≥4 months)

3.3.2 Effect of plant species diversity and planting density for plant growth, overall flowering succession and dynamic change

From the observation of quadrat charts, it was shown that plant species diversity may affect overall flowering succession and dynamic change. When a low diversity of species was used, overall flowering tended to be shorter and with less dynamic change. For example, in Quadrat 1 (Low diversity and Low density), the impression over time had been similar for 10 months and the overall flowering season was limited for two months. On the contrary, for high plant species diversity, there were more possibilities to have a longer flowering term, seasonal interest and dynamic change. For example in Quadrat 29 (High diversity, Low density), the different growth pattern of species and leaf texture produced more dynamic change and seasonal interest and they was 10 months of overall flowering season.

It seems that the strength of the interaction is often planting density dependent. In low planting density, individual plants generally produced better growth than those in high planting density because they had enough space and there was less competition. For example, the creeping species of *S. uniflora* was able to cover a larger area in the low planting density in Quadrat 5, whereas its growth was restricted when the species was planted in the high planting density in Quadrat 3. In the high planting density, it was observed that plants had more interaction. For example, in Quadrat 4, *P. saxifraga* showed better growth after the growth of *F. glauca* was reduced, presumably through competition. The same tendency was observed between *F. glauca* and *S. byzantina* 'Silver Carpet' in Quadrat 12.

The important finding was that above tendencies were not only because of plant species diversity and planting density but were affected strongly by the species which were used. It is possible to have more dynamic change and extend overall flowering time in a limited species diversity if the species of different growth patterns and flowering time were used (e.g. Quadrat 4, Quadrat 17). However, they had a limited flowering term and produced a uniform visual impression if the species of similar growth pattern of species and same flowering season were used although there may have been a higher number of species (e.g. Quadrat 30). Planting density seems to be an important factor when the different growth types and growth patterns of species are used. When the creeping habitat of species was planted in high planting density, they have less competition (e.g. Quadrat 7, Quadrat 11). However, although in low planting density, if many species which have similar growth patterns were used, the competition between plants could be high (e.g. Quadrat 6, Quadrat 19). These explanations are summarized in Table 5.11.

Table 5.11 Summary of the effect of plant species diversity and planting density for plant growth, aesthetics and dynamic change and related individual characteristics

		Interaction between plants	Overall flower succession	Dynamic change
Plant species diversity	High	-	Longer	More
	Low	-	Shorter	Less
Planting density	High	Higher	-	-
	Low	Lower	-	-
Individual plant characteristics to affect these categories		Growth type and growth pattern	Flowering term and season	Growth type and growth pattern

3.4 Quadrat study 2 (Colonization)

In each quadrat, the number of weeds and self-seeding planted plants were counted. For weed colonization, the effect of plant species diversity and planting density, mulch (with and without) and planting aspect (NE, NW, SE, SW) were studied. It is worth noticing that the substrate depths are different with and without mulch, 10 cm and 20 cm respectively. In addition, the relationships between weed invasion and the percentage of bareground, and weed invasion and the percentage of planting cover were investigated. For self-seeding, the total number of self-seeding over time in total of 32 quadrats was investigated.

3.4.1. Weeds colonization

A limited species of weeds (9 species) were observed on this roof. They were *Capsella bursa-pastoris, Cerastium fontanum, Epilobium montanum, Geranium molle, Picris echioides, Poa annua, Senecio jacobea, Sonchus oleraceus* and *Taraxcum officinale.* Their life form, habitat, phenology and dispersal are summarized in Table 5.12.

The total number of weeds occurring over time is shown in Table 5.13. A high number of weeds was found until July but it decreased after August. Three species, *C. bursa-pastoris, E. montanum* and *S. jacobea* were the most commonly found. The result showed that individual species had different colonization peak times. *C. bursa-pastoris* showed the highest number in the winter-spring and the number reduced dramatically in the summer. *E. montanum* and *S. jacobea* showed higher number in the early summer. On the contrary, the number of *G. molle* and *P. echioides* increased in the autumn.

The effect of plant species diversity and planting density on the mean frequency of weeds per quadrat over time is shown in Table 5.14. At first, there was a significant effect of plant species diversity. Interestingly, the larger number of weeds was observed in high plant species diversity. However, planting density became more important for weeds invasion as time passed. Overall, high planting density was able to reduce the number of weeds. Especially, the tendency was observed that the combination of low plant species diversity and high planting density had smaller number of weeds whereas the high plant species diversity and low planting density showed higher number of weeds.

The effect of mulch on the mean frequency of weeds per quadrat over time is shown in Table 5.15. It was clear that the combination of gravel mulch and shallow substrate was effective to reduce weeds invasion. The weeds number was smaller in mulch areas than in no-mulch although there were exceptions in August and November.

The effect of aspect on the mean frequency of weeds per quadrat over time is shown in Table 5.16. In all months, there was no significant effect of the aspect. However, the tendency was observed that the north side, particularly the NW showed the high frequency of weeds whereas the SE showed the smaller number of weeds.

The relationship between bare ground and total number of weeds and relationship between total plants coverage and total number of weeds per quadrat on 12th October are shown in Fig.5.9 and Fig.5.10 respectively. Bare ground was measured on 11th July as well, however, the same tendency was observed, therefore, only results from 12th October are shown. In both instances, no significant relationship was observed. These results might suggest that not only bare ground and coverage of plants, but other factors such as plant structures may also affect weeds invasion.

Table 5.12 Characteristics of weeds which were found on the roof

	Life form	Habitat	Phenology	Dispersal
C. bursa-pastoris	Summer or winter annual herb, Native	Disturbed, fertile soil	Variable, since germination may occur throughout most of year. Plants are capable of overwintering. Flowers most abundant from May to October and seed set mainly from June to October.	wind, rain wash, birds
C. fontanum	Perennial herb, Native	All types of unshaded dryland habitat	Winter green. Flowers April to September. Seed shed from June onwards	-
E. montanum	Perennial herb, Native	Widely distributed on rocky, disturbed shaded ground	Overwintering as short above- or below-ground stolons. Flowers June to August and set seeds from June to September	Wind
G. molle	Winter- or more rarely, summer-annual, Native	Mainly recorded from limestone outcrops and distributed wide habitats with bare ground such as wasteland and pasture.	Variable, dependent upon season of germination. Autumn-germinating plants overwinter as a rosettes. Flowers within the period April to September and sets seed from June to October.	Ballistic
P. echioides	Annual or biennial herb, possibly introduced	Waysides, hedgebanks, filed margins, rough places and costal	It is an autumn or spring germinating plant. Spring/summer flowering but can flower at any time of the year.	Wind
P. annua	Short lived perennial, Native	Occurs in a great variety of disturbed situation, but most common on arable land and disturbed fertile soil	Leaves, flowers and fruits may be found during all seasons. Most typically summer annual but can behave as winter annual in droughted habitats.	-
S. jacobea	Perennial herb, Native	Widely dispersed, especially in rocky habitat, but restricted to habitats with at least a little bare ground.	Seeds germinate mainly in autumn and seedling overwinter in a leafy condition. Some seeds germinate in spring. Ripe seed dispersed from August until winter.	Wind
S. oleraceus	Winter- or summer annual, Native	Frequently recorded from demolition sites and widespread on disturbed places.	Autumn-germinating plants overwinter as rosettes, spring-germinating plants as achenes. Flowers and fruits from May onwards in autumn-germinating and June onwards in spring-germinating plants	Wind
T. officinale	Perennial, Native	A common constituent	A small rosette of leaves overwinters.	wind

		of all but aquatic habitat.	Flowers from May to October but mainly April to June. Most seeds set from May to June.	

(Adapted from Klingman,,et al.,1982 and Grime,et al. 1988)

Table 5.13 Total number of individual weeds over time (total number of 32 quadrats)

	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov
C. bursa-pastoris	478	442	448	306	224	159	35	23	16	5
C. fontanum	0	18	6	10	9	3	1	0	11	0
E. montanum	40	42	59	68	148	132	20	30	34	44
G. molle	0	0	0	0	0	0	0	12	11	10
P. echioides	1	3	1	2	41	39	33	46	66	54
P. annua	1	5	2	4	3	3	5	1	3	1
Senecio jacobea	118	120	137	144	123	67	35	101	46	69
S. oleraceus	2	9	8	4	3	3	1	0	10	1
T. officinale	1	0	0	0	0	0	0	1	0	2
Total	641	639	661	538	551	406	130	214	197	186

Table 5.14 Mean number of weeds per quadrat over time

(Effect of plant species diversity and planting density) (n=8)

		Feb	March	April	May	June	July	Aug	Sep	Oct	Nov
High diversity	High density	22.63 ab	24.13 a	16.38 ab	15.88 ab	23.50 a	16.88 a	2.63 a	3.00 a	2.50 a	3.63 a
	Low density	31.50 a	30.50 a	29.25 a	25.25 a	18.75 a	15.63 a	5.88 a	9.63 a	8.63 a	8.38 a
Low diversity	High density	11.88 b	13.63 a	15.50 b	10.75 b	8.00 a	5.88 a	2.13 a	5.13 a	4.25 a	3.25 a
	Low density	16.13 ab	16.63 a	24.00 ab	18.00 ab	20.25 a	12.38 a	6.00 a	9.38 a	9.13 a	7.75 a
	Probability	Diversity P<0.05 S.E=±5.07	ns S.E=±6.38	Density P<0.01 S.E=±3.52	Density P<0.05 S.E=±3.70	ns S.E=±4.43	ns SE=±4.17	Density P<0.01 S.E=±1.53	ns SE=±3.12	Density P<0.01 S.E=±1.62	Density P<0.01 S.E=±1.84

P=Probability, SE=Standard Error, Letters of Tukey multiple comparison are compareing values within a colum (each month) Means with the same letter do not differ significantly from each other.

Table 5.15 Mean number of weeds per quadrat over time (Effect of mulch) (n=16)

	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov
No mulch	26.56 a	28.50 a	22.06 a	20.94 a	23.63 a	16.25 a	3.69 a	9.06 a	6.94 a	5.44 a
Mulch	14.50 b	13.94 b	20.50 a	14.00 a	11.63 b	9.13 a	4.63 a	4.50 a	5.31 a	6.06 a
Probability	P<0.05 S.E=±3.63	P<0.05 S.E=±4.28	ns S.E=±2.81	ns S.E=±2.72	P<0.01 S.E=±3.00	ns S.E=±2.91	ns S.E=±1.14	ns S.E=±2.17	ns S.E=±1.31	ns S.E=±1.39

P=Probability, SE=Standard Error, Letters of Tukey multiple comparison are compareing values within a colum (each month) Means with the same letter do not differ significantly from each other.

Table 5.16 Mean number of weeds per quadrat over time (Effect of aspect) (n=8)

	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov
NE	11.87 a	22.25 a	20.00 a	14.25 a	24.25 a	4.63 a	6.13 a	6.13 a	4.63 a	3.13 b
NW	21.00 a	22.88 a	27.50 a	21.75 a	21.88 a	20.63 a	5.00 a	11.88 a	8.38 a	10.25 a
SE	26.25 a	19.88 a	16.38 a	12.50 a	11.63 a	11.25 a	2.13 a	2.88 a	3.25 a	4.25 ab
SW	23.00 a	19.88 a	21.25 a	21.38 a	12.75 a	14.25 a	3.38 a	6.25 a	8.25 a	5.38 ab
P	ns S.E=±5.43	ns S.E=±6.83	ns S.E=±3.83	ns S.E=±3.89	ns S.E=±4.49	ns S.E=±3.90	ns S.E=±1.57	ns S.E=±3.06	ns S.E=±1.75	ns S.E=±1.76

P=Probability, SE=Standard Error, Letters of Tukey multiple comparison are compareing values within a colum (each month) Means with the same letter do not differ significantly from each other.

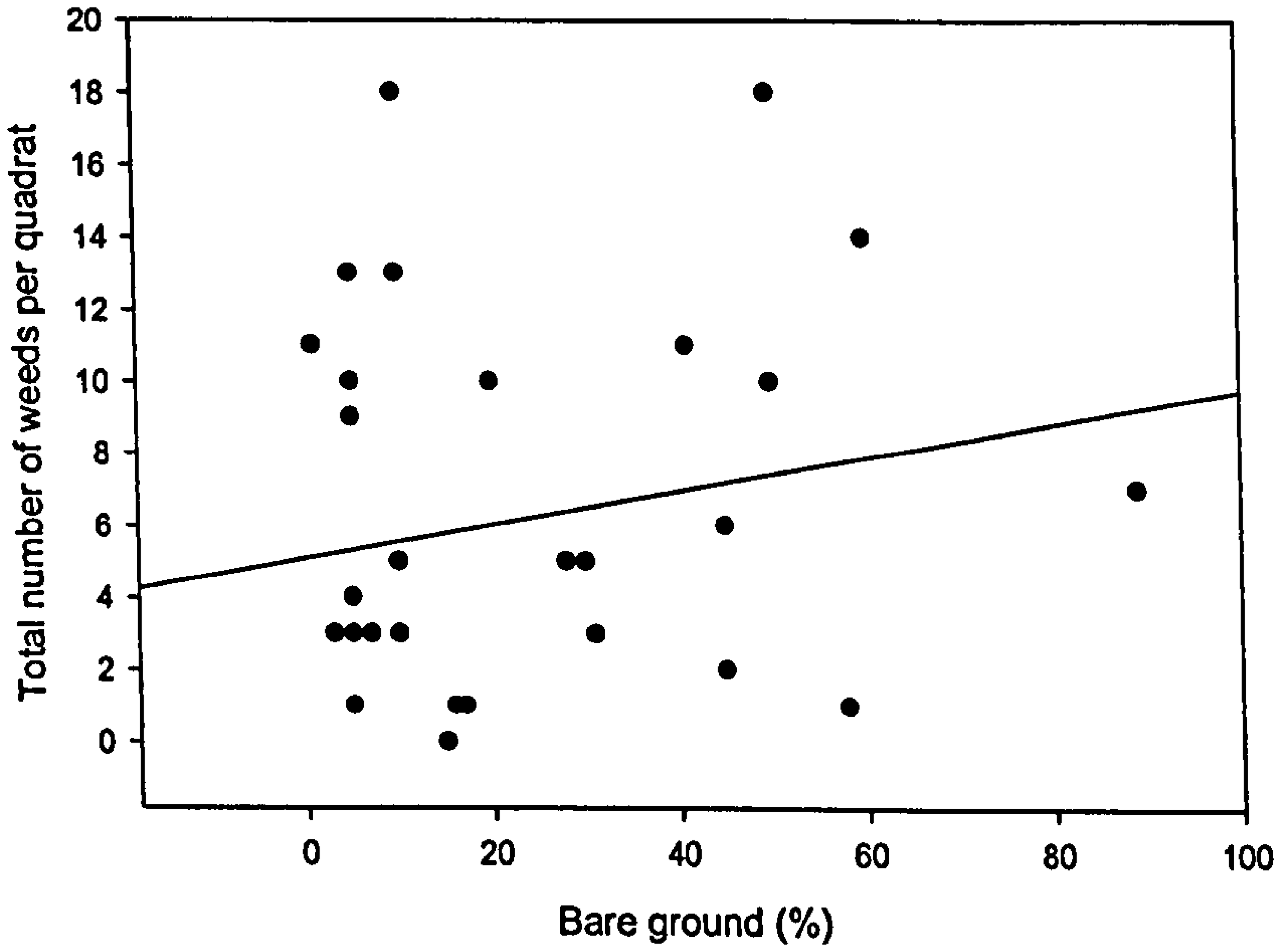


Fig. 5.9 Relationship between bare ground and total number of weeds per quadrat on 12th October (y= 5.09 + 0.047 X, R^2=3.8%, P=0.28>0.05)

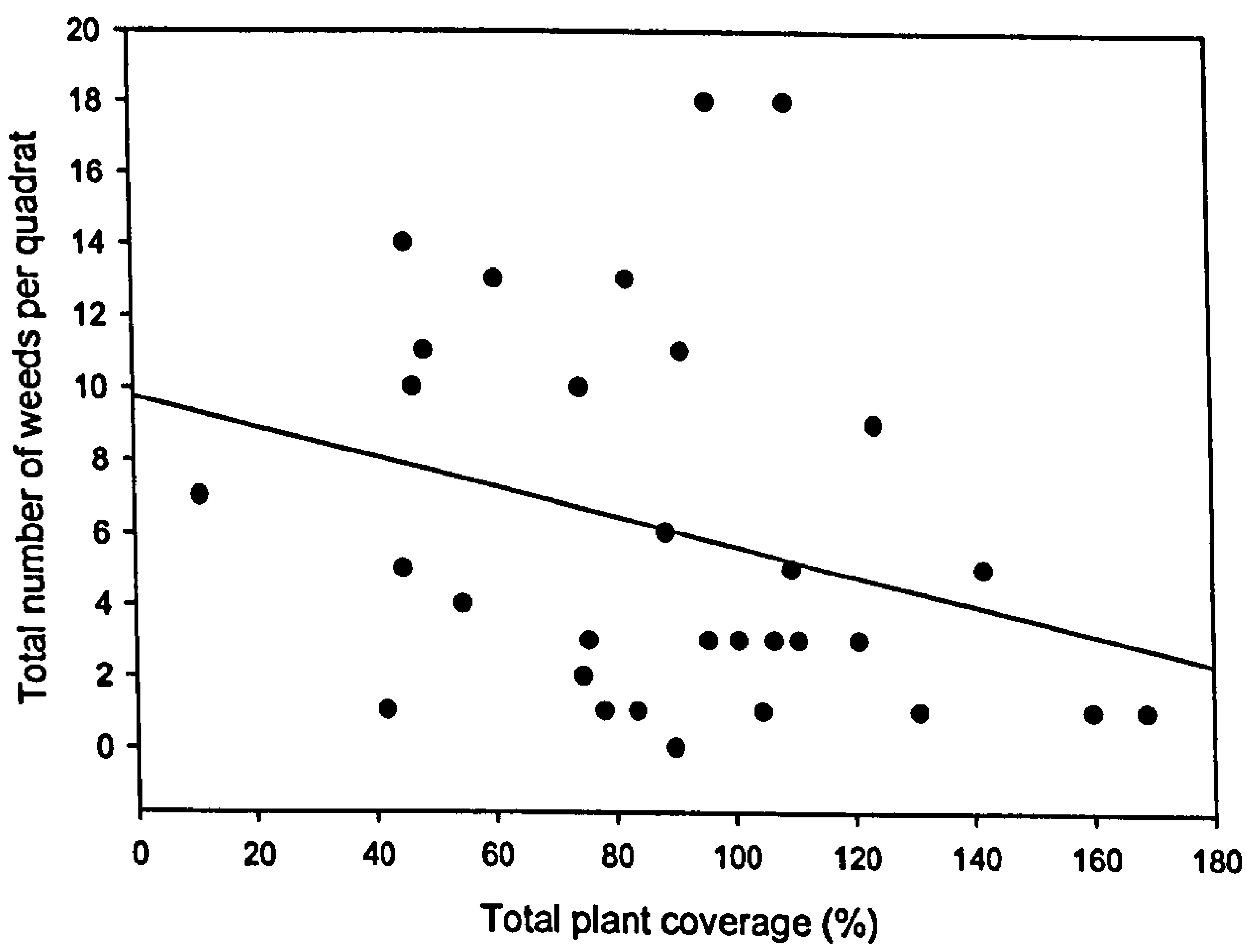


Fig.5.10 Relationship between total plant coverage and total number of weeds per quadrat on 12th October (y=9.77-0.041x,R^2=8.1%, P=0.12>0.05)

3.4.2 Self-seeding

During the experiment, 30 species which showed self-seeding were found in 32 quadrats. The total number of self-seeded plants found in 32 quadrats over time is shown in Table 5.17. This result indicates that the seeds of many plant species used on this green roof are not dormant and they germinate easily. Especially, *A. schoenoprasum, C. rotundifolia, Festuca* spp. and *P. saxifraga* showed very high number of seedlings after flowering in the autumn. It is worth pointing out that not only the number of self-seeding but also their survivability, establishment and growing speed might be an important factor for the performance of green roofs. It was observed that self-seeding of *E. manescavii, E.cyparissias* 'Fens Ruby' and *Festuca* spp. established well and grew fast and these species could be invasive. Especially, when these species were planted near low planting density areas, many big self-seeding were observed (Quadrat 30). On the contrary, some species of seedling such as *O. laevigatum* 'Herrenhausen' and *Sedum* spp. grew slowly and they may not disturb the other planting.

Table 5.17 Total number of self-seeding over time (total number of 32 quadrats)

	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov
A. schoenoprasum	0	0	21	36	18	22	569	10300	10400	3052
A. amellus	3	0	0	0	22	25	24	15	28	32
C. nepeta	0	0	3	0	0	4	113	87	65	103
C. rotundifolia	1	0	0	10	9	9	19	34	240	2492
D. deltoides	9	24	35	80	107	109	93	55	49	56
E. manescavii	25	29	55	80	76	106	78	119	149	173
E.cyparissias 'Fens Ruby'	0	0	15	55	50	50	51	60	39	53
Festuca spp.	397	840	622	1210	445	460	398	628	3019	3365
G. verum	0	0	0	7	2	2	6	8	0	1
G. endressii 'Wargrave Pink'	0	0	0	0	0	0	0	1	0	1
G.*repens* 'Dorothy Teacher'	0	0	0	0	11	3	0	0	0	0
K. 'Border Ballet'	0	0	0	0	0	0	1	4	101	167
L. x superbum	3	0	0	0	17	24	18	41	53	50
M. ciliata	0	0	0	0	0	0	0	0	1	540
N. x faassenii	0	0	0	0	0	0	0	0	1	0
O. *laevigatum* 'Herrenhausen'	0	1	0	0	0	1	10	11	87	202
P. saxifraga	0	12	46	47	20	30	35	15809	11082	6407
P. veris	0	2	1	0	0	0	0	0	0	0
P. vulgaris	0	0	0	0	1	1	0	0	0	0
S. acre 'Golden Queen'	10	4	21	28	22	21	39	51	25	24
S. album 'Coral Carpet'	6	11	14	18	11	11	11	15	11	7
S. hispanicum 'Silver Carpet'	3	4	11	27	25	16	15	14	13	14
S. kamtschaticum var. *floriferum* 'Weihenstehaner Gold'	0	0	0	0	1	1	0	0	0	0
S. sexangulare	0	4	12	23	3	3	4	3	7	7
S. *arachnoideum*	0	0	2	2	3	3	1	1	0	0
S. uniflora	0	1	0	1	10	5	1	0	0	5
S. *byzantina* 'Silver Carpet'	0	0	2	2	2	5	5	32	41	46
S. *tenuissima*	117	356	145	216	57	72	80	70	80	527
V.*phoeniceum*	0	0	0	0	1	1	1	2	0	1

4. Discussion

4.1 Overview and plant performance

Overall plant growth and flower performance on Moorgate Croft Business Centre green roof were successful and showed the seasonal interest throughout a year. This results indicates that it is possible to install an attractive garden on a roof with 20cm of substrate with little supplemental watering and little maintenance. To reduce the maintenance and achieve effective long lasting contributions, it may be better to plant rhythmical repetition of various themes within the overall design using wide range of different species. A structure of dominant herbaceous plants to give impact would be called 'theme plants'. These plants are distinguished by their striking habits and help them to stand among a mass of other perennials. Many drought tolerant plants form a low carpet, therefore, it would be effective to put the taller perennials among them (Hausen and Stahl, 1993). Moorgate Croft Business Centre green roof used rhythmical plantings, *S. striatum* and *S. tenuissima* and seed head of *S.* 'Herbstfreude' worked as 'theme plants' in the winter time.

Compare to the typical mature plants cultivate in an appropriate site, height and diameter of most species on the roof were within the range of those of typical mature plants, although they tend to be small, especially in diameter probably because exposure of limited substrate depth, drought and high wind on the roof. This phenomenon tends to be observed when plants are grown in containers. In all plant species used in this study, only two species, *S. arachnoideum* and *S. spathulifolium* var. *purpureum* showed weak growth and poor flower performance. Generally, *Sempervivum* spp. are well suited to extensive green roofs because they are well adapted to very dry conditions and shallow soils and traditionally have been grown on slate and tile roofs and walls (Dunnett and Kingsbury, 2004a). It was not clear why poor growth was observed on this roof, but it may be because of the competition with other plants. It was observed that the growth of *S. spathulifolium* var. *purpureum* was particularly restricted during the summer on this roof, therefore, they might be not able to stand the high temperature. In a previous study, *S. spathulifolium* var. *purpureum* showed the weak growth in high temperature (30°C) (Nagase and Thuring, 2006).

Janzen (1967) and Gentry (1974) pointed out that there were two patterns of plant flowering: species which flower massively for a brief period and species in which a constant small production of flowers occurred over a long period. Mass flowering has the presumed advantage of attracting many pollinators, while sequential flowering may reduce the level of geitonogamy (fertilization between neighbouring flowers on the same plant) and force the pollinators to fly between plants (Primback and Lloyd, 1980). In this study, some species such as *S. uniflora, E. ciliatum, S. kamtschaticum* var. *floriferum* 'Weihenstephaner Gold' produced a large number of flowers and they flowered one after another and they are particularly valuable for providing aesthetic for green roofs. 6 species (*A. schoenoprasum, A. maritima* 'Splendens', *G. verum, G. cinereum* 'Ballerina', *M. ciliata* and *N.* x *faassenii*) flowered again in the autumn after they finished flowering completely in the spring and these species also showed a long flowering term. This phenomenon is observed in some species (e.g. *Achillea* spp.) when the plants are mown soon after midsummer on a ground (Kingsbury, 1996). It was estimated that because of high temperature and drought on the roof over the summer 2006, the plants may have experienced the same effect as cutting back (Dunnett, personal communication).

On the contrary, the bulb spp., grass spp. and most of *Sedum* spp. used in this experiment had a short flowering period in this study. Especially, for the bulb spp., the number of flowering shoots was also limited. However, it is important to remember that these species play an important role for the performance of green roofs. Bulbs flower at the time when small number of species is flowering. Grass spp. provide attractive foliage throughout a year. *Sedum* spp. are drought tolerant and provide beautiful foliage colours in winter. In many cases, a limited number of species can be used for extensive green roofs because of thin substrate, low cost and low maintenance, therefore, it is necessary to consider the flowering performance as well as their seasonal interest. It is important to study flower performance for over years because there is a high possibility that the flowering performance may be different from years. Petanidou, et al.(1995) studied the flowering phenology in a phryganic (East Mediterranean Shrub community) for 4 consecutive years and it was shown that the start of flowering of a species is statistically correlated with the temperature in the previous month, not with rainfall. The summer in 2006 in Rotherham was unusually warm and it is necessary to compare the flower performance with the other year.

Many species used in this experiment were self-seeding. In Chapter 3-1 Germination study, it was shown that most of potential use for extensive were non-dormant and the maximum germination occurred in the shortest time when provided with optimum temperature and sufficient water (Probert, 2000). The tendency was observed that the species which had high germination rate in the experiment of Chapter 3-1 Germination study showed a high number of self-seeding in this study as well. For example, *A. schoenoprasum, Festuca* spp. and *P. saxifraga* had high germination rate in the spring (96.7%, 63.3% and 76.7% respectively) and they showed high number of self-seeding in this study. Previous studies supported that these species can be self-seeding on green roofs (Dunnett and Kingsbury, 2004a, Koehler, 2006). However, there were some exceptions. For example, the germination rate of *C. rotundifolia* was low in the previous experiment (23.3%), however, they showed high self-seeding this time. The opposite phenomenon was observed in *N.* x *faassenii* (96.7% in the previous experiment). This maybe because of number of seeds which the plants produced and competition with other species. This study was too short to say whether the germinated plants survived over winter and become established. According to previous studies, regeneration by seed is an occasional event with most seedlings eliminated by competition from the surroundings established vegetation (Grubb, 1997, Morgan, 1995). It was observed that self-seeded plants of *E. manescavii, E.cyparissias* 'Fens Ruby' and *Festuca* spp. established well and they grew fast, therefore, these species could be invasive. *Festuca* spp. established within the plants of *E. ciliatum* and they would be difficult to remove. Further observation of plants invisibility is required to confirm whether it is better not to use these species or cutting is necessary after their flowering to prevent spreading their seeds.

4.2 Effect of aspect

In this study, there was no significant effect of aspect on overall growth. One of the reasons for this might be that the roof did not completely face to the four directions and this might relieve environmental stresses of certain exposures. There is one study about the relation of geometry, vegetation and thermal comfort around buildings in urban settings using simulation. It was shown that the NE and the SW allowed a better adaptation of the place to summer and winter thermal comfort conditions than the other directions (Masmoudi and Mazouz, 2004). Another reason for no significant difference may be that they experience many cloudy days in the Northern England and direction is of lesser importance in cloudy than in clear conditions because they increase diffuse radiation (Rosenberg et al., 1983).

However, there was a tendency that overall plant growth was better in the NE and the SE. It was also observed that many species started to flower from the SE and some long flowering species flowered over winter only in the SE. This may be related with higher soil temperature of these directions. Aspect affects soil temperature and soil heat flux since capture of radiation is determined in part by this factor (Rosenberg et al., 1983). Hedberg (1964) reports that from an ecological point of view the diurnal cycle is very important since the screening of direct sunlight causes a rapid decrease in temperature. According to Jackson (1966), spring and early summer flowering species are most closely correlated with temperature, while late summer and fall species are

most closely correlated with photoperiod. Many plants used in this study belong to the former, therefore, temperature might be important for flower development for them. Dunne et al. (2003) also showed that warmer temperatures in the Rocky Mountain region, subalpine meadow species, including graminoides, forbs, and shrubs, are likely to flower much earlier and for slightly longer periods, with particularly strong effects seen in early flowering species. However, generally, soil moisture was generally not a significant explanatory factor for either timing or duration of flowering. In this study, the longest mean flower term was shown in the NW, however, the reason is not very clear.
In this study, there was significant effect of planting aspect in a small number of species. *F. amethystina, F. glauca, G. lucidum a* showed the better growth in the north whereas *S. spathulifolium* var. *purpureum* showed the better growth in the south. Probably the former three species can adapt in partial shade place (Brickwell, 2003) and they would prefer the higher moisture positions than sunny dry areas. On the contrary, some Sedum spp. showed better performance in the south probably because they can adapt to dry places and grow well in warmer places. *P. veris* grow open sunny places naturally, however, they are shade tolerant plant. It was hypothesized that *P. veris* would grow better in the north because of their higher moisture positions. However, *P. veris* showed better growth in the south. According to Hitchmough (1994a), the habitat environment does not always represent the physiological optimum, however, in general, species are likely to be most robust and easy to cultivate where planting site and natural environment are broadly similar.

4.3 Effect of plant species diversity and planting density

As previous authors pointed out (Dunnett and Kingsbury, 2004a, Dunnett 2004b), plant communities were more likely to have a longer flowering time, seasonal interest and dynamic change in higher plant species diversity in this study. However, the important finding of the current study was that these characteristics were not only because of plant species diversity (number of plants) itself but also were related to the growth pattern, flowering season and texture of leaves of used plant species. In many cases, extensive green roofs required a shallow substrate (less than 10cm), low maintenance and low cost and this permits the use of only a limited number of species such as the plants which belong to Pattern 1 and Pattern 2. Even though the limited plant species can be used, it is possible to have more dynamic change and extend the overall flowering time if the species are carefully chosen. Snodgrass (2005) divided commonly used species for extensive green roofs into two groups: 1) ground covers (e.g. *Sedum acre* 'Aureum', *Sedum reflexum*) which persist year around and be able to live for the life of the roof and 2) plants that can be used as accents (*Dianthus deltoides, Talium calycinum*) which intended to survive for the life of the roof, they still must be compatible with the growing medium for the duration of their installation. This is from the experience from the nursery which provides the green roof plants and it is the same as the classification of plant growth pattern described in here. There is the tendency that people notice only survivability of plants because of harsh environment of green roofs. However, if only just choosing drought tolerant plants may be difficult to create aesthetic and seasonal interesting green roofs. Awareness of plant characteristics such as growth pattern and seasonal interest is important to extend seasonal display.

When plant planting density is decided, it is important to be aware of the combination of plant species or growth type (Height and Coverage) and growth pattern (Table 5.9, Table 5.10). This is supported by Hitchmough (1994a). Spacing between groups of different herbaceous species is more critical due to varying growth rates and habits. If manageable stability is to be achieved by the edges of two species it is important to consider respectively canopy heights, predilection to flop or make rapid lateral growth, timing of growth commencement in spring, shade-tolerant of foliage of the smaller species etc. Plant interactions could be positive (e.g. mutualism, commensalism) and negative (e.g. competitive). The environmental factors constraining plant growth or survival is one that can be alleviated by the physical presence of another plant through an amelioration of the conditions of the external environment (Brooker and Callaghan, 1998). This strength of the interaction is often planting density dependent (Callaghan and Emanuelsson, 1985). Examples of positive interaction include improvement of microclimate by taller plants shade and limit evaporative soil water loss, and water retention by mosses. In this study, however, it was difficult to tell about positive interaction between plants although plant competition was observed. This study was carried out by the observation of actual green roofs and the combination of plant density and plant species diversity was too varied to make clear comparisons. Moreover, the duration of the experiment might be too short to detect plant interactions. Therefore, continuation of the monitoring is necessary to investigate how planting density affects plant growth.

4.4 Weeds colonization

Only 9 species of weeds were found on the extensive green roof and their sizes tended to be small. This may be because that the weeds on this roof were regularly removed. Many flowers of *C. bursa-pastoris* were observed, therefore, this species may spread the seed itself on the roof. However, most plants of the other species did not flower, therefore, they germinated gradually or their seeds might keep coming into the roof. In the previous study by Dunnett and Nagase (2007), more than 35 species were identified, however, a small number of dominant species such as *Agrostis stolonifera*, *Vicia hirsuta, Taraxcum officinale* colonized at 10cm and 20cm depth of green roof in Sheffield UK. The species were the not exactly the same ones as in this experiment, however, the weeds which were found in these two areas were typical weeds of cultivation and wasteland and a mix of native species and exotic or naturalized taxa, which is typical of the cosmopolitan nature of spontaneous urban plant communities.

A large number of weeds were identified until July, however after August, the number decreased significantly. This result suggests that weeding from spring to summer is particularly important. Hitchmough (2004b) suggested that weed competition is most damaging when it occurs at the time when supplies of a resource becoming limited. The water demands of desirable and weed species are likely to be greatest during periods of extension growth. According to the growth pattern of planted species, most species started to grow vigorously from April and reached to the best growth before August. Therefore, the weeding in this period is important to reduce competition with weeds.

Generally, it is believed that plant species diversity confers resistance to invasion because more diverse assemblages more fully utilize available resources, thus leaving little resource space for individual of new species (Levine and D'Antonio, 1999). In this study, however, a tendency was observed that the larger number of weeds colonized in areas of high plant species diversity although there was significant effect of plant species diversity only in February. Indeed, more recent theoretical studies consistently supported the predicted negative relationship between plant species diversity and invasibility, although the results of empirical studies were decidedly mixed (Levine and D'Antonio, 1999). Understanding how invasibility varies with plant species diversity is complicated by the fact that variation in plant species diversity is controlled by, and thus covaries with disturbance, resource availability, physical stress, competitors, consumers, etc, the same factors known to influence invisibility (Rejmánek, 1989, Huston 1994, Robinson et al. 1995, Wiser et al. 1998). It may be too early to say that weeds would be always found in higher plant species diversity and further research is necessary to confirm this. For example, other factors may come into play – areas of high planted diversity also coincided with greater substrate depths: therefore more weeds could be supported. Also, areas of low planting diversity may have different surface mulches that deter weed invasion.

A high planting density (the coverage of more than 50 %) was able to reduce weed invasion significantly. This is supported by Rao (1999) who mentioned that increasing planting density by using a higher seedling rate and narrower planting spacing is an important weed management technique as it enhances planted species competitiveness by suppressing or smothering weeds. Higher plant populations create shading which prevents weed seed germination, emergence and establishment. A higher plant population is, however, dependent on growth habit, leaf orientation, duration and other characteristics. Indeed, the result of this study suggested that not only a low percentage of bare ground and high percentage of plants cover, but other factors such as plant structure also affect weeds invasion. In this study, it was impossible to identify what are important factors to reduce weeds invasion, hence, further experiment is required.

In this study, a tendency was observed that the north side, especially the NW showed the high frequency of weeds whereas the number of weeds was smaller in the SE. Since most of weed species found in this study were dispersed by wind, therefore, this result may be related to wind direction. Previous research showed that dispersal is predominantly in a direction reflecting the prevailing winds. Nadeau and King (1991) studied the seed dispersal of *Linaria vulgaris* using seed traps. Four traps 50 cm apart were aligned following each of eight directions around each flowering stands. The result showed that 25 % of seeds fell on the SE sides of the stands, following the predominant wind currents. Auld (1988) showed that the most successful spreading species *Carduus tenuiflorus* between the other two species of *Avena fatua* and *Onopordum acanthium* appeared to be strongly influenced by wind speed and direction. Unfortunately, the wind direction was not measured in this study and further study might be necessary to prove this.

As hypothesized, it was shown that the gravel mulch could reduce weed invasions. The area with the gravel mulch is shallower than without mulch, therefore, also might help to reduce weed invasion because the shallow substrate is generally drier than the deep substrate. However, the number of weeds in the mulch was significantly lower than those in the non-mulch area for only three months. Probably, the rate at which weeds can colonise the surface of a gravel mulch might be higher than other mulch materials. Indeed, according to Hitchmough (2004a), the most effective mulches for restricting colonisation via weed seed rain are synthetic materials such as polythene woven weedmats, followed by very coarse grades of bark, wood chips, and coarse mineral aggregates. Therefore, if it is required to reduce more weeds invasion, it is necessary to consider choosing the appropriate materials as well as cost and design of green roofs.

5. Conclusion

It was concluded that it was possible to create aesthetic extensive green roofs which has a long flowering and seasonal interest with little maintenance and supplemental irrigation if the appropriate plants were chosen. Almost all plant species used in this study showed good growth and flower performance. Throughout 9 months, at least 3 species flowered and the highest number of flowering species was observed in June. *S. uniflora, E. ciliatum, S. kamtschaticum* var. *floriferum* 'Weihenstephaner Gold' and *C. nepeta* showed particularly long flowering performance. Only two species, *S. arachnoideum* and *S. spathulifolium* var. *purpureum* showed weak growth and poor flower performance. It was shown that plant species diversity may affect overall flowering succession and dynamic change. In areas of high plant species diversity, there were more possibilities to have a longer flowering term, more seasonal interest and dynamic change than low plant species diversity. In areas of low planting density, individual plants generally produced better growth than those in high planting density, whereas in areas of high planting density, there was more likelihood to have plant interaction. However, these tendencies were not only because of plant species diversity and planting density itself but it was affect strongly by the combination of species which were used. Therefore, it is important to be aware of individual growth characteristics such as plant size (coverage and vertical), phenological growth pattern and flowering term. There was no significant difference between aspects in both of plant growth and flower performance. However, the tendency of the better growth in the NE and the SE and longer flower duration was shown in the NW whereas many species started flower from the SE. Only 9 species of weeds were found on this green roof. The total number of weeds decreased dramatically from August, therefore, Spring-Summer weeding is particularly important. The combination of low plant species diversity and high planting density could reduce weeds effectively. The high frequency of weeds was found in the NW whereas the number of weeds was smaller in the SE probably because of wind direction. Using a gravel mulch in shallow substrate could reduce the number of weeds significantly. Many species used in this study were self-seeding and *A. schoenoprasum, C. rotundifolia, Festuca* spp. and *P. saxifraga* showed very high numbers of seedlings. Although the amount of self-seeding was not high, the self-seeding of *E. manescavii, E. cyparissias* 'Fens Ruby' and *Festuca* spp. established well and grew fast and these species could be invasive. Such information would be useful for selection of plant species, planting design and maintenance for further extensive green roof instalment. In future studies, it is necessary to collect the data of continuous moisture into substrate, temperature and wind direction in different places on a roof to analyze the plant growth accurately. Moreover, a long term study of plant performance (especially flower performance) and weed invasion are required to understand how they are different from year to year.

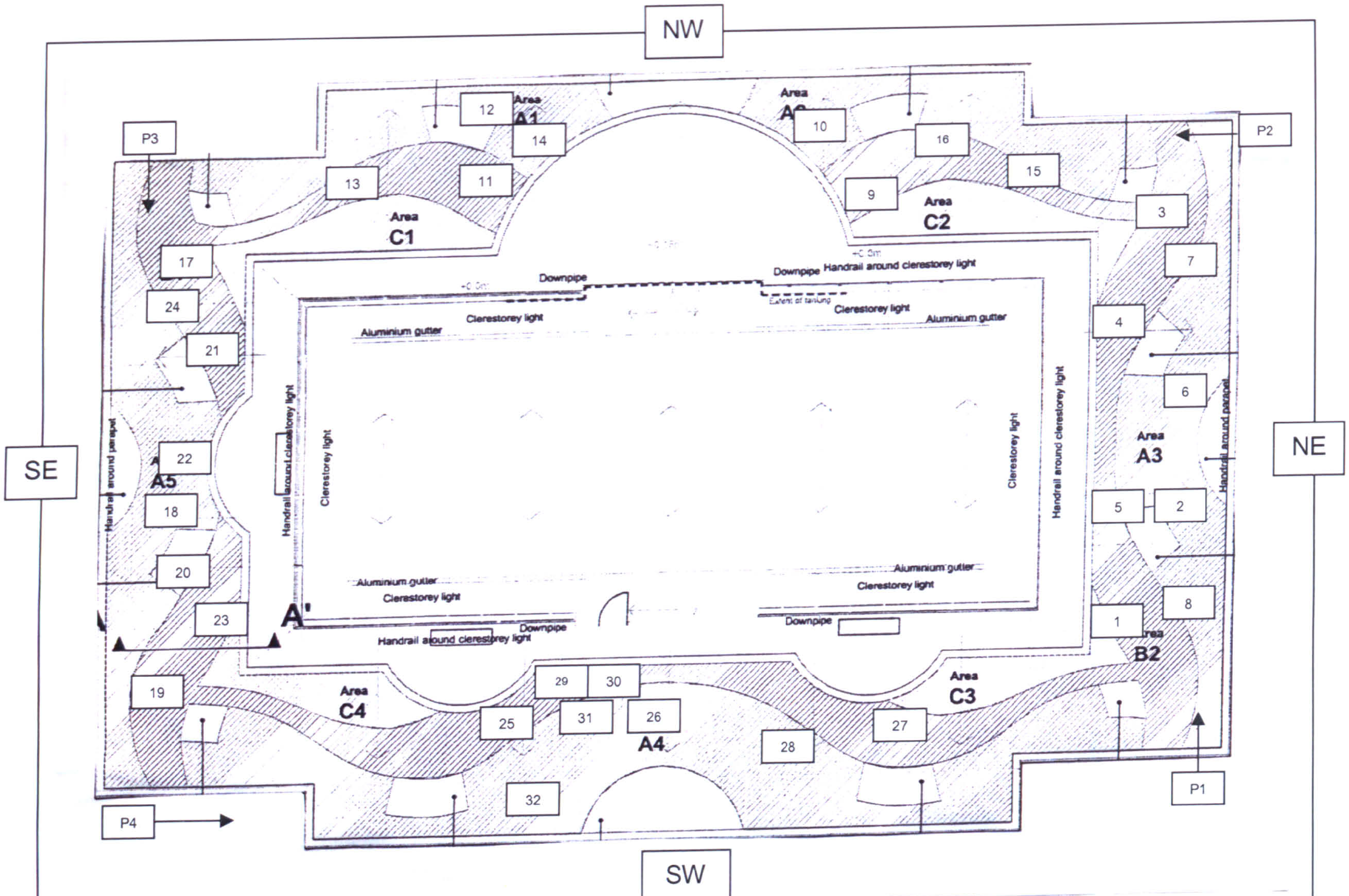


Fig. 5.1 Positions where photographs were taken for overview and 32 quadrats

A: semi-extensive mix, B: alpine mix, and C: low-edge mix
P is the positions where photographs for overview are taken and Number in Fig. indicates the number of quadrat

Table 5.1 The change of overview in the NE

20th January 2006	8th February 2006	17th February 2006	22nd March 2006	12th April 2006
				
21st April 2006	3rd May 2006	25th May 2006	8th June 2006	14th June 2006
				

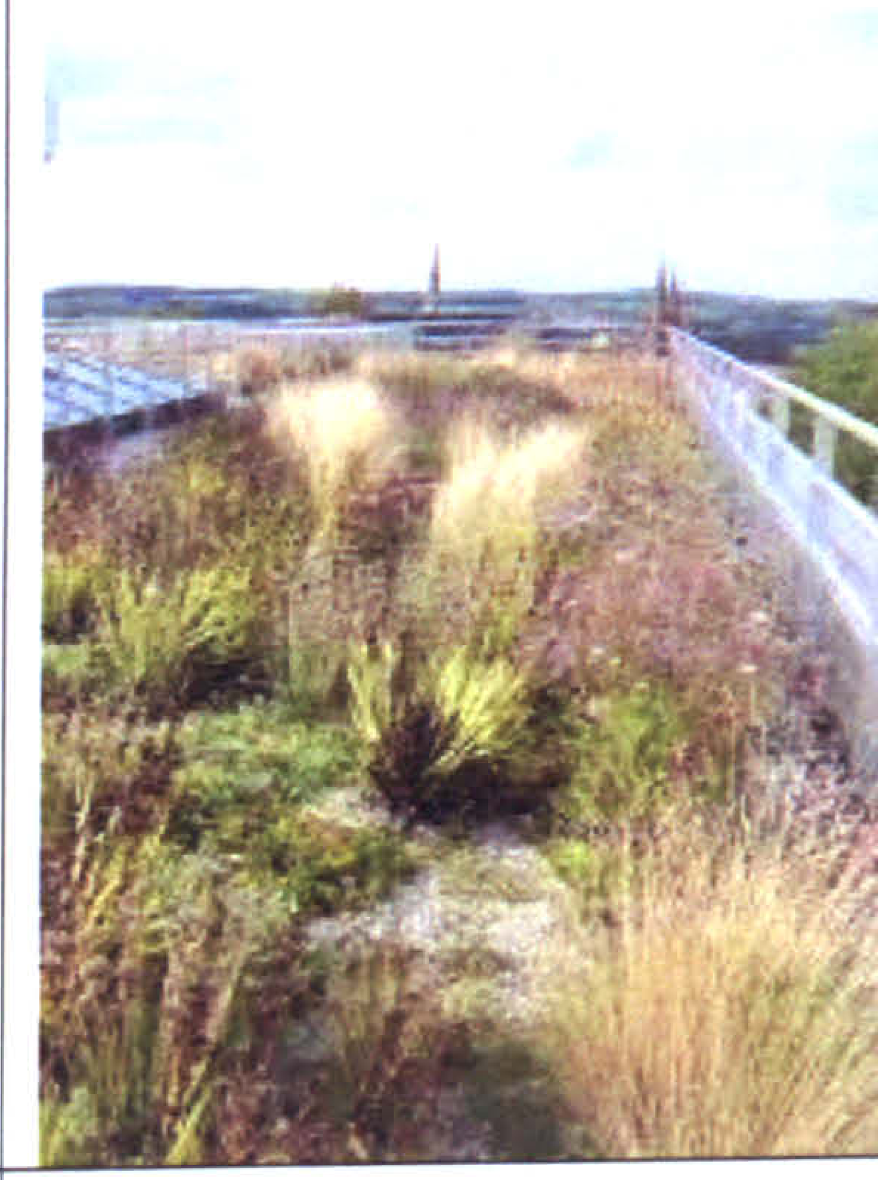
27th June 2007

14th July 2006

27th July 2006

8th August 2006

22nd August

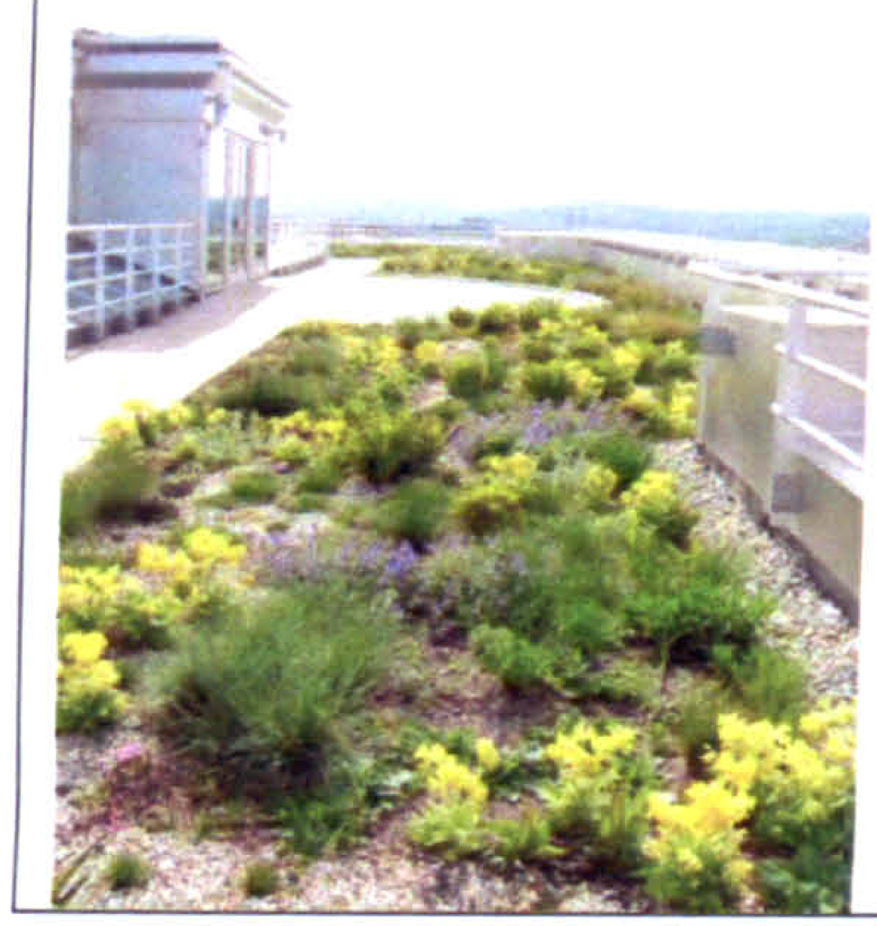


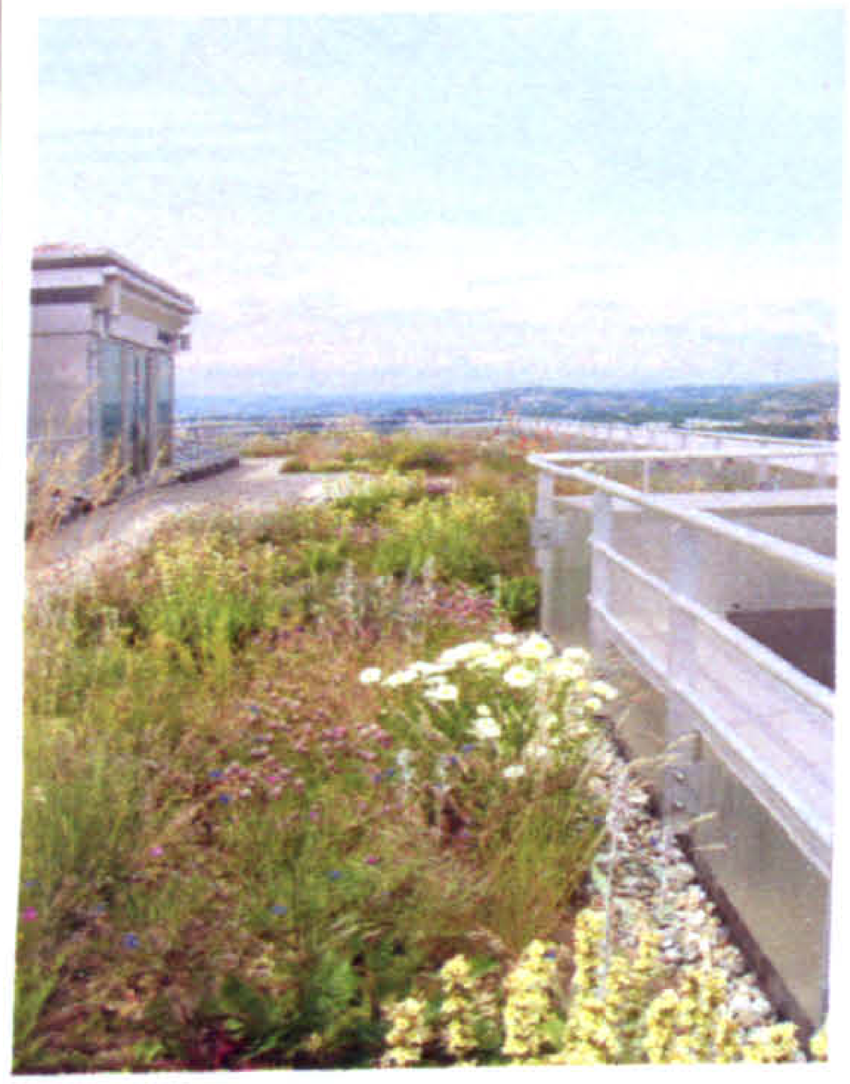
6th September 2006

27thSeptember 2006

15th November 2006

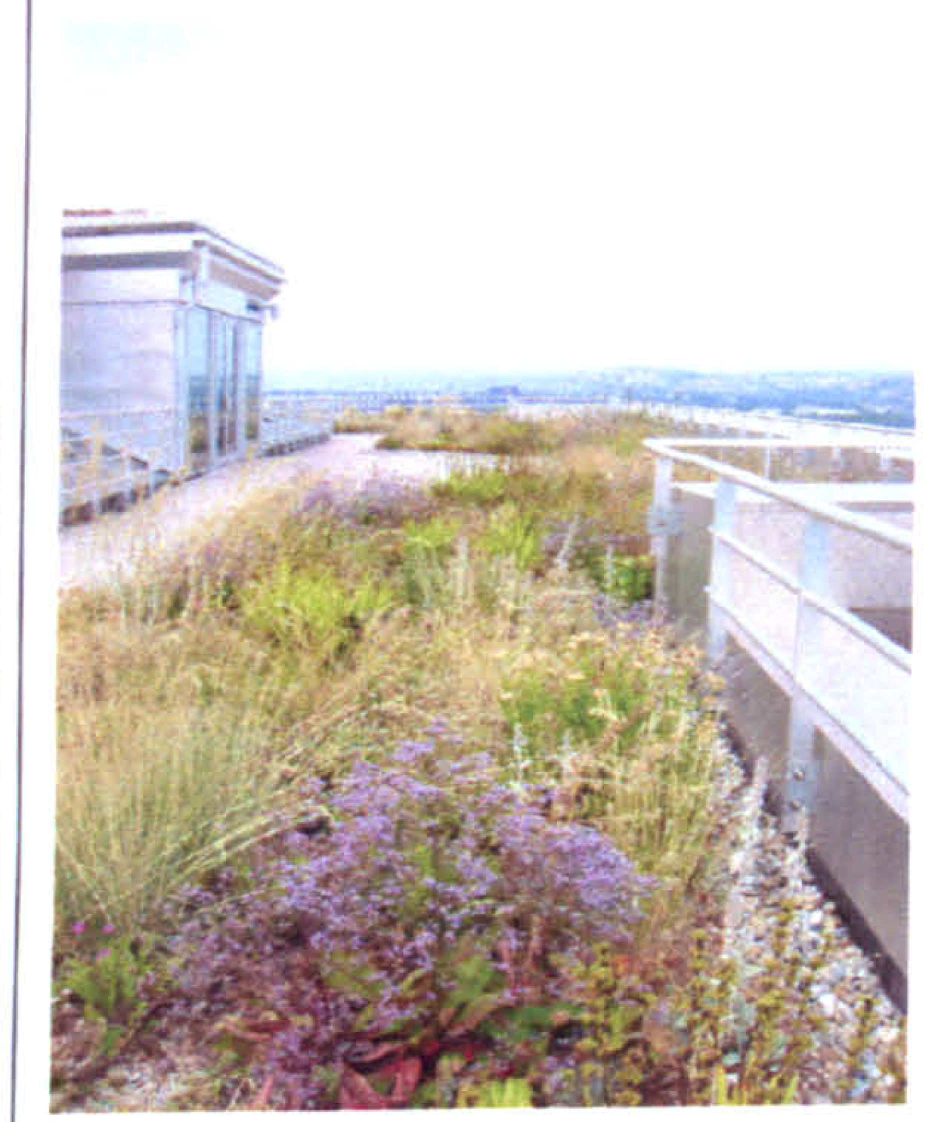
Table 5.2 The change of overview in the NW

20th January 2006 	8th February 2006 	17th February 2006 	22nd March 2006 	12th April 2006 
21st April 2006 	3rd May 2006 	25th May 2006 	8th June 2006 	14th June 2006 



27th June 2007

14th July 2006



27th July 2006

8th August 2006

22nd August 2006

6th September 2006

27thSeptember 2006

15th November 2006

Table 5.3 The change of overview in the SE

20th January 2006	8th February 2006	17th February 2006	22nd March 2006	12th April 2006
				
21st April 2006	3rd May 2006	25th May 2006	8th June 2006	14th June 2006
				

27th June 2007

14th July 2006

27th July 2006

8th August 2006

22nd August 2006

6th September 2006

27thSeptember 2006

15th November 2006

Table 5.4 The change of overview in the SW

20th January 2006	8th February 2006	17th February 2006	22nd March 2006	12th April 2006
				
21st April 2006	3rd May 2006	25th May 2006	8th June 2006	14th June 2006
				

27th June 2007

14th July 2006

27th July 2006

8th August 2006

22nd August 2006

6th September 2006

27thSeptember 2006

15th November 2006

Table 5.9 Flowering characteristics of individual plant species

		February		March		April		May		June		July		August		September		October		November	
A. caeruleum	P									100											
	S									2.2											
	Q									3											
A. karataviense	P								100.0												
	S								1												
	Q								2.8												
A. schoenoprasum	P				8.3	8.3	8.3	8.3	83.3	100.0						58.3	66.7	50	75	8.3	8.3
	S				0.1	0.2	0.1	0.1	3.9	48						1.4	1.3	0.9	1	0.1	0.1
	Q				0.1	0.1	0.1	0.1	2.5	4.1						0.8	0.8	0.6	0.8	0.1	0.1
A. juniperifolia	P						91.7	100													
	S						4.4	15.4													
	Q						1.2	3.3													
A. maritima 'Splendens'	P		8.3	8.3					91.7	100.0	58.3	50.0	33.3	41.7	25.0	16.7	8.3	25.0	25.0	25.0	25.0
	S		0.1	0.1					6.4	12.3	1.6	1.1	0.7	0.5	0.3	0.2	0.1	0.3	0.6	0.6	0.5
	Q		0.1	0.1					2.9	3.2	0.8	0.7	0.3	0.4	0.3	0.2	0.1	0.3	0.3	0.5	0.3
A. amellus	P												58.3	83.3	100.0	100.0	100.0	91.7	25.0		
	S												2.4	2.8	4.8	6.3	7.7	3	1.1		
	Q												1.2	2.1	2.4	3.6	3.9	1.4	0.3		
C. nepeta	P											100.0	100.0	100.0	100.0	75.0	41.7	33.3	33.3	16.7	25.0
	S											34.5	39.2	33.8	30.3	8.5	2.8	3.8	4.1	0.5	0.4
	Q											2.6	3.1	2.8	2.3	1	0.4	0.7	0.8	0.2	0.2
C. rotundifolia	P	8.3	8.3							66.7	100.0	100.0	50.0	41.7	41.7	58.3	25.0	16.7	16.7		
	S	0.3	0.3							3	7.4	4.6	0.8	0.8	0.9	1	0.3	0.2	0.2		
	Q	0.2	0.2							1.2	2.9	2.3	0.7	0.6	0.8	0.7	0.3	0.2	0.2		
C. scabiosa	P										91.7	75.0	16.7								
	S										7.8	7.4	0.2								
	Q										2.8	2.9	0.2								
C. tommasinianus 'Whitewell Purple'	P					100															
	S					1.2															
	Q					1.7															
D. deltoides	P									100.0	100.0	66.7									
	S									29.3	28.7	3.7									
	Q									3.4	3.3	0.9									
E. ciliatum	P								91.7	100.0	100.0	91.7	100.0	100.0	100.0	100.0	100.0	91.7	83.3	16.7	16.7
	S								8.5	22	30.7	23.2	25.8	18.3	17	18.3	15.5	10.7	2.7	1.3	0.7
	Q								2	3.5	3.3	3.1	3.3	3.1	3	3.3	2.4	2.1	1.3	0.3	0.3

E. manescavii	P						8.3	8.3	100.0	100.0	75.0	41.7	33.3	83.3	91.7	91.7	41.7	16.7			
	S						0.1	0.1	8.4	5.5	1.8	0.9	0.5	2.8	3.4	2.2	0.8	0.2			
	Q						0.2	0.1	2	2.4	1.1	0.5	0.3	2.2	2.3	1.9	0.8	0.2			
E. cyparissias 'Fens Ruby'	P							100	100	100											
	S							28.7	46.7	37.8											
	Q							2.6	3.1	4.5											
F. amethystina	P								100	100											
	S								138.3	135.9											
	Q								2.9	3.5											
F glauca	P								100	100											
	S								173.7	166.3											
	Q								3.3	3.8											
G. verum	P										100.0	83.3	75.0			66.7	58.3	25.0	8.3	8.3	
	S										73.8	54.4	1.7			3.4	4.8	1	0.5	0.1	
	Q										3.8	2.3	0.7			3.8	0.8	0.3	0.1	0.1	
G. cinereum 'Ballerina'	P	8.3	8.3	8.3	8.3	8.3				100.0	33.3	75.0	75.0	50.0	83.3	83.3	25.0			8.3	8.3
	S	0.2	0.2	0.3	0.2	0.2				14.8	1.5	2.6	2.2	0.9	2.8	1.8	0.5			0.2	0.1
	Q	0.1	0.1	0.1	0.1	0.1				3.6	0.7	1.2	1.1	0.8	2	1.3	0.4			0.1	0.1
G. lucidum	P								100.0	100.0	66.7										
	S								35.9	14.9	2.7										
	Q								3.3	2.3	1.2										
G. endressii 'Wargrave Pink'	P									100.0	100.0	83.3	8.3		33.3	16.7	8.3				
	S									8.8	6.2	2.1	0.1		0.6	0.2	0.1				
	Q									2.5	2.7	1.2	0.1		0.3	0.2	0.1				
G. repens 'Dorothy Teacher'	P									100.0	41.7		75.0	75.0	83.3	75.0	75.0	8.3			
	S									21.8	1.6		1.8	2.3	7.5	8.6	6.1	0.1			
	Q									3	0.6		0.8	0.8	2.3	1.4	1.3	0.1			
H. nummularium 'Wisely primrose'	P									100.0	50.0	25.0									
	S									4.8	2	0.7									
	Q									1.9	1.3	0.4									
H. sempervirens	P									100	100										
	S									32.1	32.4										
	Q									3	2.3										
K. 'Border Ballet'	P									58.3	91.7	91.7	16.7								
	S									0.8	1.4	1.7	0.2								
	Q									2.2	2.3	1.9	0.4								
L. angustifolia 'Hidcote'	P										100.0	100.0	25.0								
	S										6	11.5	0.3								
	Q										3	2.8	0.3								
L. x superbum	P										100.0	100.0	58.3								

	S										13.6	19.2	1.8								
	Q										3.3	3.9	0.6								
L. latifolium	P										41.7	75.0	91.7	100.0	75.0						
	S										2.3	3.4	3.7	3.1	1.5						
	Q										1.4	2.8	3.7	2.8	1.3						
M. ciliata	P									100	100						100	100	100		
	S									58	57.3						1	0.8	0.6		
	Q									2.9	3.3						0.5	0.3	0.3		
M. armeniacum	P						100	100													
	S						1.3	1.4													
	Q						2.8	3.2													
N. x faassenii	P						75.0	100.0	100.0	100.0						58.3	58.3	33.3	33.3		
	S						7.4	28.9	39.5	9.6						1.9	3.4	2.8	0.8		
	Q						1.2	3.1	3.6	1.3						0.8	0.8	0.5	0.4		
O. laevigatum 'Herrenhausen'	P											100.0	100.0	100.0	100.0	100.0	33.3				
	S											16.3	26.2	18.8	16.2	10.2	1				
	Q											2.7	4.5	2.9	1.9	1.5	0.3				
P. saxifraga	P										100.0	100.0	100.0	100.0	100.0	100.0	100.0	75.0	83.3		
	S										205.2	228.5	45	120.8	223.7	162.1	32.3	10.8	6.5		
	Q										4.1	3.3	1.5	2.3	3.3	3.3	1.3	0.8	1		
P. douglasii	P								91.7												
	S								27.2												
	Q								2.1												
P. veris	P	33.3	33.3	75.0	75.0	100.0	100.0	100.0	58.3												
	S	0.3	0.4	0.8	1.3	1.7	12.1	16.8	2.6												
	Q	0.3	0.3	0.8	1	1.5	4.3	4.9	0.6												
P. vulgaris	P						58.3	100.0													
	S						1.1	1.9													
	Q						1.8	2.7													
S. x sylvestris `Blauhügel'	P									100.0	100.0	100.0	50.0	41.7	58.3	50.0	33.3				
	S									13.2	13.4	10.3	2.1	1.3	2.2	1.2	0.5				
	Q									3.7	3.3	1.3	0.5	0.4	0.6	0.5	0.3				
S. acre 'Golden Queen'	P										100	25									
	S										59.3	0.4									
	Q										26	0.3									
S. album 'Coral Carpet'	P									50.0	100.0	8.3									
	S									18.7	38.6	0.4									
	Q									1.4	3.5	0.1									
S. kamtschaticum var. *floriferum* '	P								100.0	100.0	58.3	66.7	75.0	83.3	100.0	100.0	83.3	25.0			
	S								12.5	14.7	2.8	5.6	4.9	8.7	21.8	28.6	8.7	0.8			

Weihenstephaner Gold'	Q								2.4	1.4	0.7	0.9	1	1.7	2.4	2.6	1.2	0.3			
S.'Herbstfreude'	P																	83.3	75	91.7	
	S																	3.1	1.8	0.2	
	Q																	1.7	0.8	0.1	
S. hispanicum 'Silver carpet'	P									91.7	83.3	58.3	41.7								
	S									117.9	31.9	1.8	2.8								
	Q									2.8	1.5	0.6	0.4								
S. reflexum	P										100										
	S										18.9										
	Q										3.1										
S. sexangulare	P										100.0	100.0	91.7	41.7							
	S										79.2	133.7	2.6	0.5							
	Q										3.7	4.1	0.9	0.4							
S. spathulifolium var. purpureum	P																				
	S																				
	Q																				
S. spurium 'Queen Mantle'	P											83.3	16.7								
	S											8.3	0.2								
	Q											2	0.2								
S. telephium 'Matrona'	P													83.3	100.0	100.0	83.3	16.7			
	S													2.3	9.8	9.5	5.2	0.2			
	Q													1.1	2.7	2.8	1.1	0.2			
S. arachnoideum	P										8.3										
	S										0.1										
	Q										0.1										
S. uniflora	P								83.3	100.0	100.0	83.3	100.0	100.0	100.0	91.7	8.3	16.7	8.3	8.3	8.3
	S								16.8	87	15.3	10.5	18.1	22.1	17.3	13.2	1.3	1.3	1.3	1.8	0.9
	Q								2	3.4	1.5	1.3	2.1	1.6	1.8	1.3	0.2	0.3	0.2	0.2	0.2
S. striatum	P									100	100	58.3									
	S									20.5	22.1	3.9									
	Q									3.5	2.8	0.7									
S. byzantina 'Silver Carpet'	P										100	100	58.3								
	S										17.1	13.3	1.2								
	Q										3.4	3.2	0.6								
S. tenuissima	P										100	100									
	S										202.3	283.3									
	Q										2.9	3.3									
T. tarda	P						75.0	66.7													
	S						0.3	0.5													
	Q						0.6	1.1													

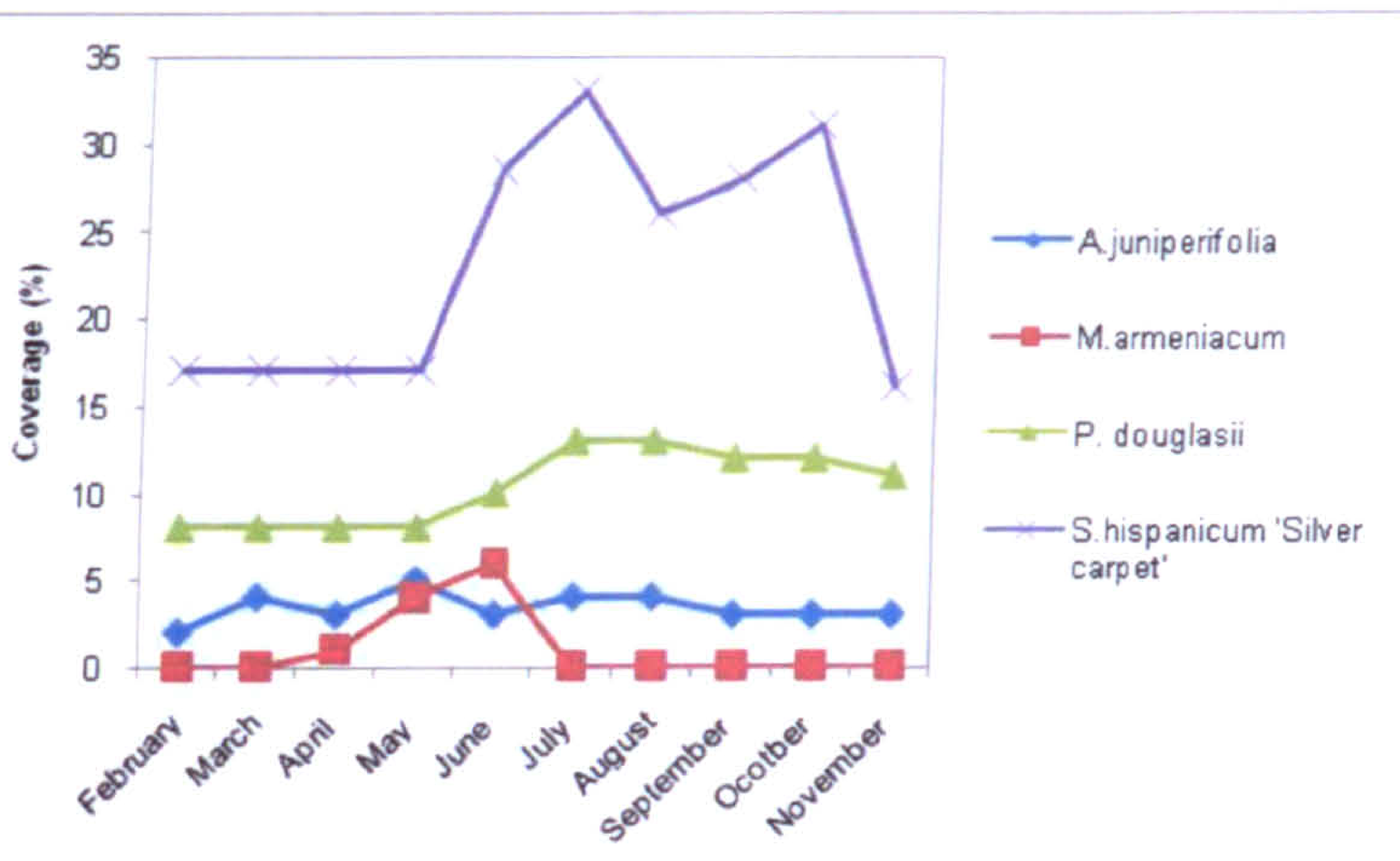
T. praestans 'Fusilier'	P							100													
	S							1.2													
	Q							2.8													
V. phoeniceum	P								100.0	75.0											
	S								2	1.1											
	Q								2.1	1											

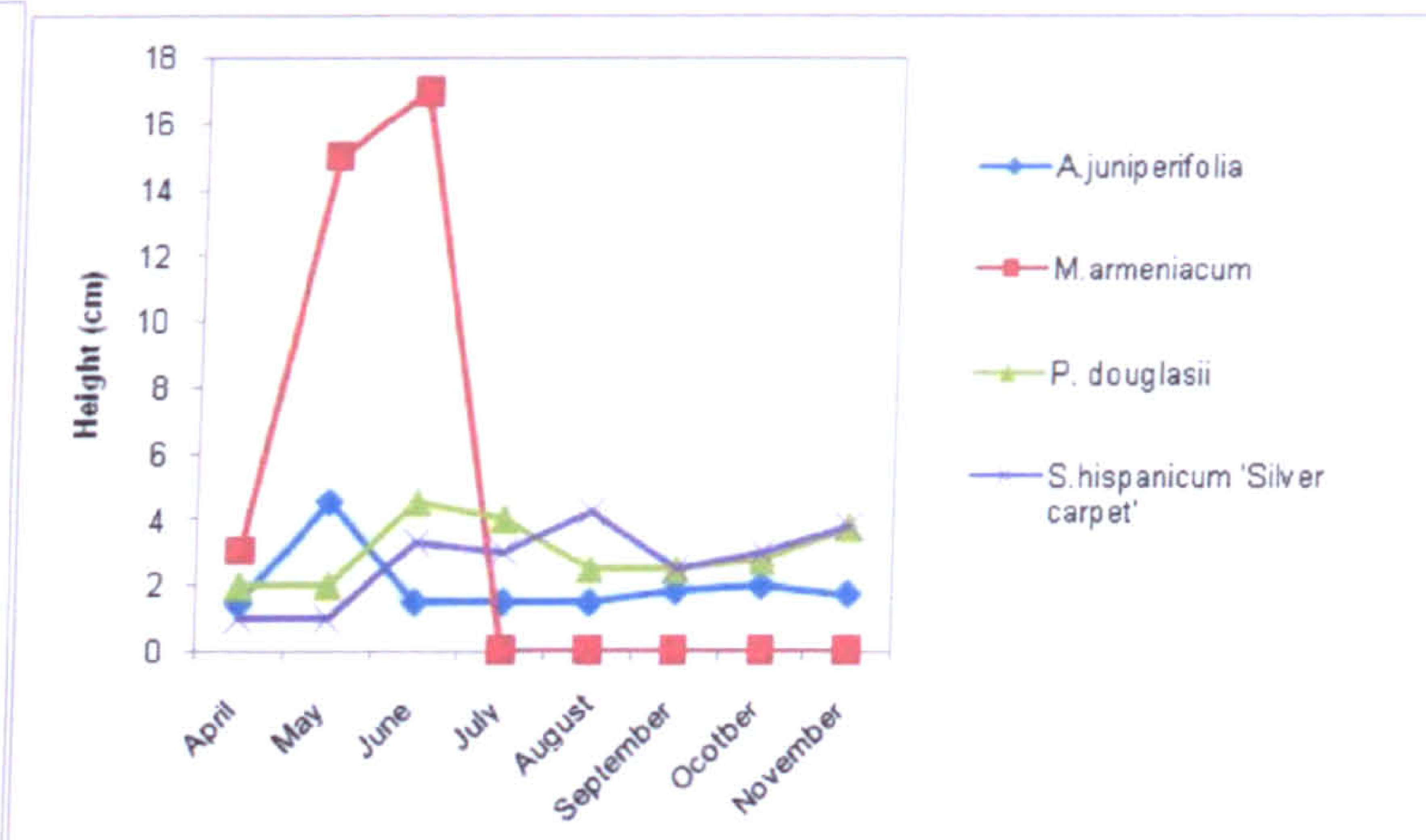
P=percentage of flowering plants, S=Mean flower shoot number, Q=Man value of appearance

Quadrat 1 (Low diversity, Low density, White, NE)

February	March	April	May	June	July	August	September	October	November

lower succession								
. juniperifolia								
I. armeniacum								
. douglasii								
. hispanicum 'Silver carpet'								



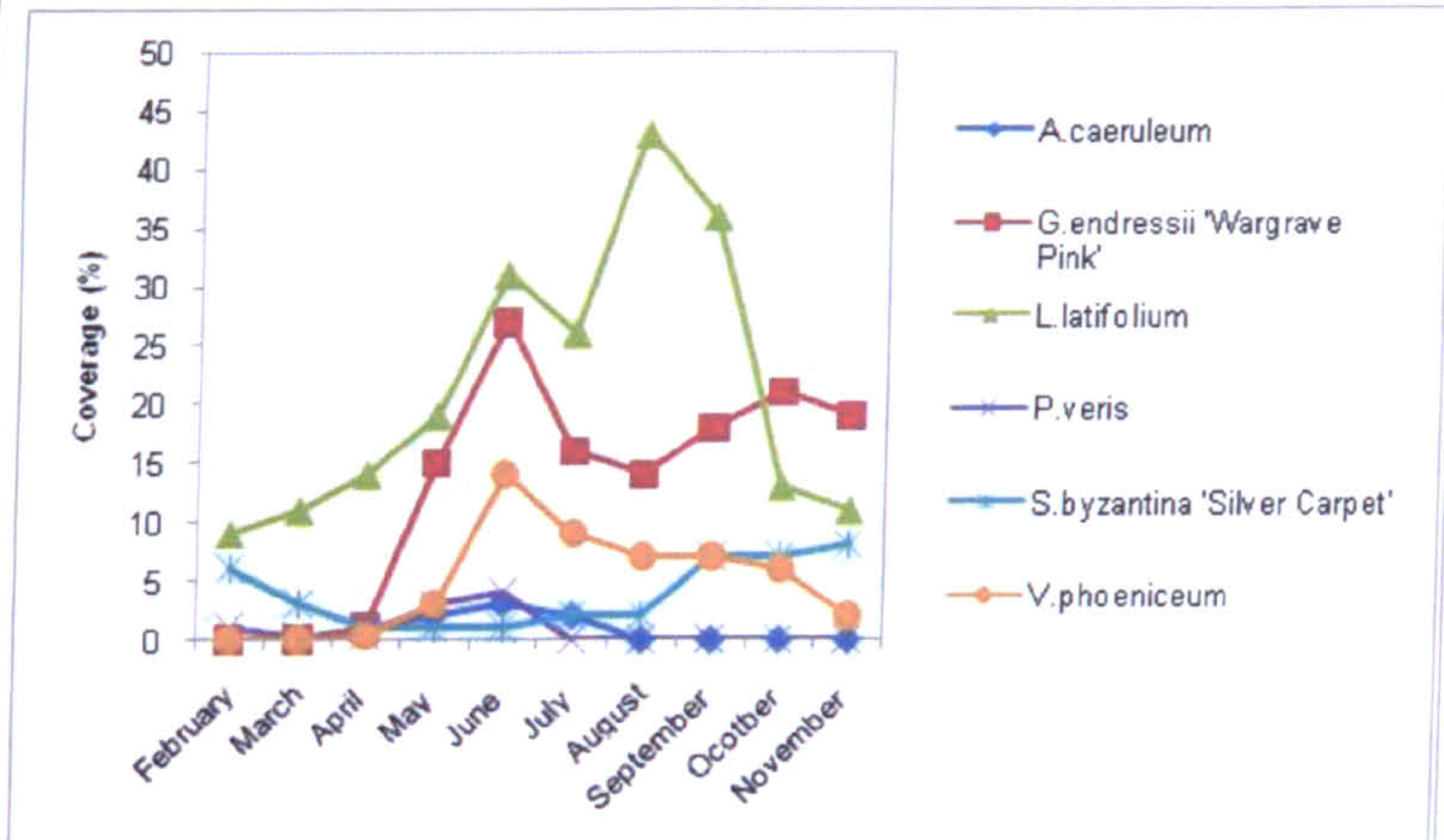


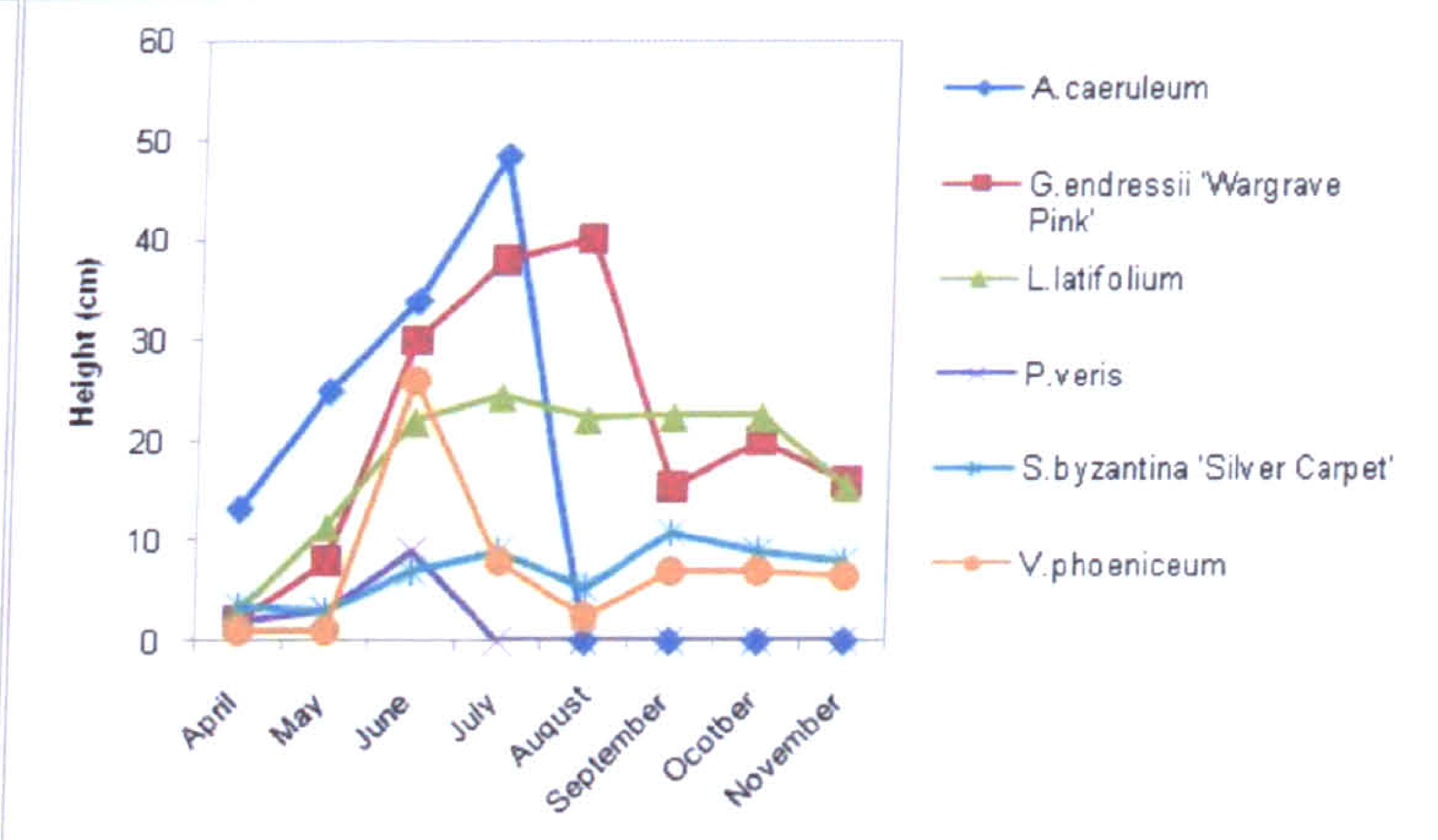
	Growth pattern
A. juniperifolia	1
M. armeniacum	2
P. douglasii	1
S. hispanicum 'Silver carpet'	1

Quadrat 2 (Low diversity, Low density, Red, NE)

February	March	April	May	June	July	August	September	October	November

Flower succession								
A. caeruleum								
G. endressii 'Wargrave Pink'								
L. latifolium	No flower							
P. veris	No flower							
S. byzantina 'Silver Carpet'	No flower							
V. phoeniceum								



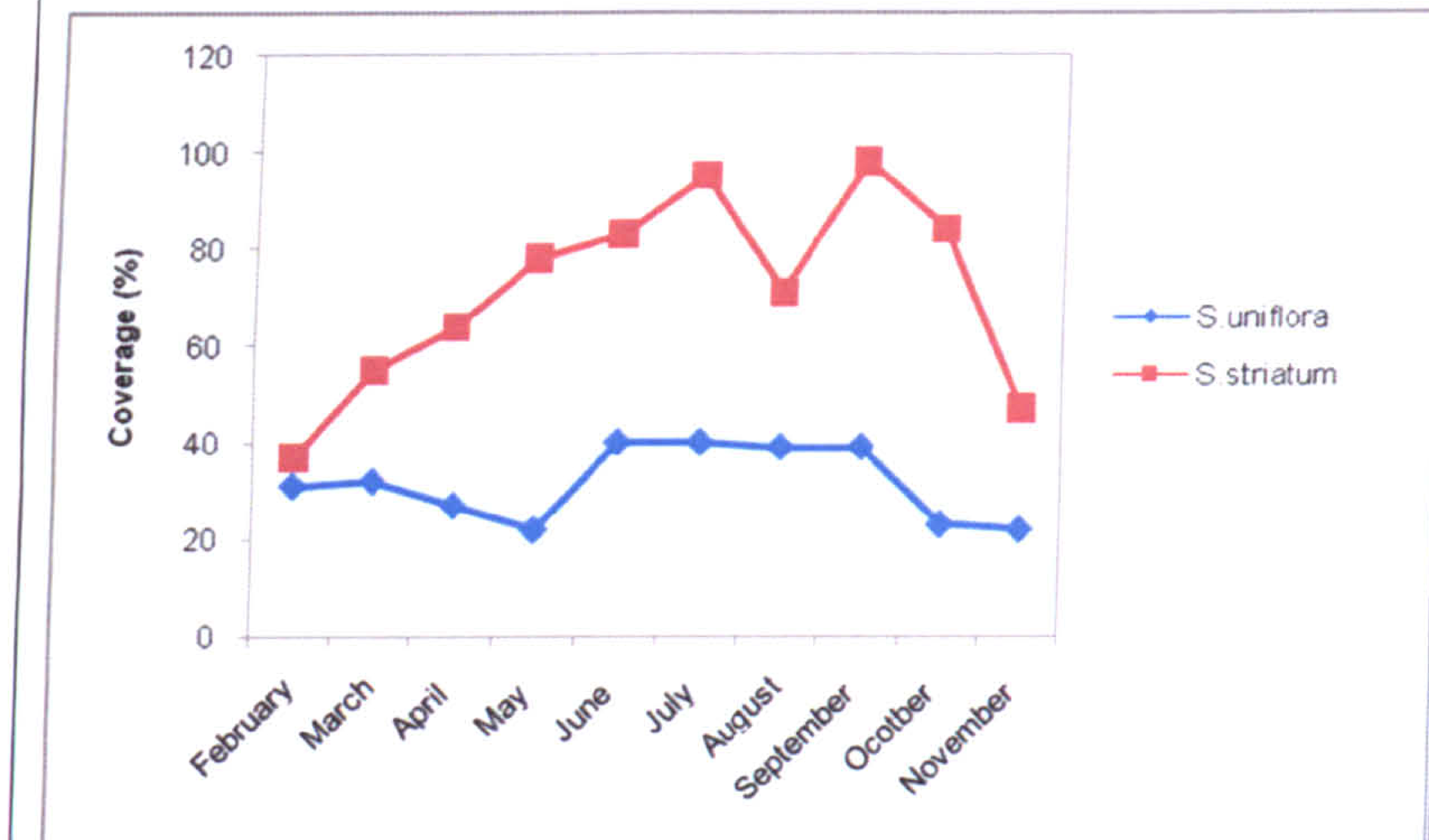


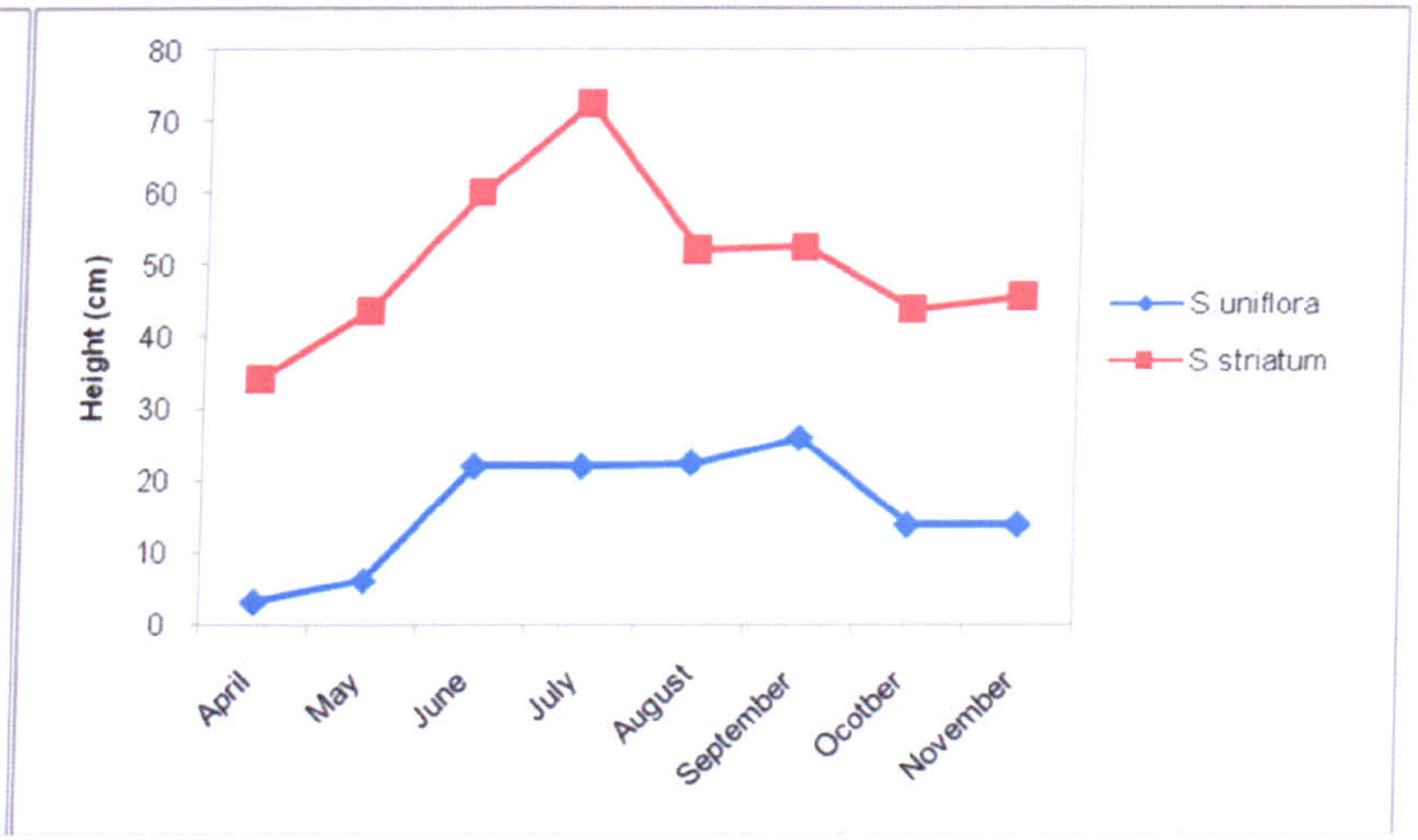
	Growth pattern
A. caeruleum	3
G. endressii 'Wargrave Pink'	3
L. latifolium	3
P. veris	1
S. byzantina 'Silver Carpet'	5
V. phoeniceum	3

Quadrat 3 (Low diversity, High density, White, NE)

February	March	April	May	June	July	August	September	October	November

Flower succession									
S. uniflora									
S. striatum									



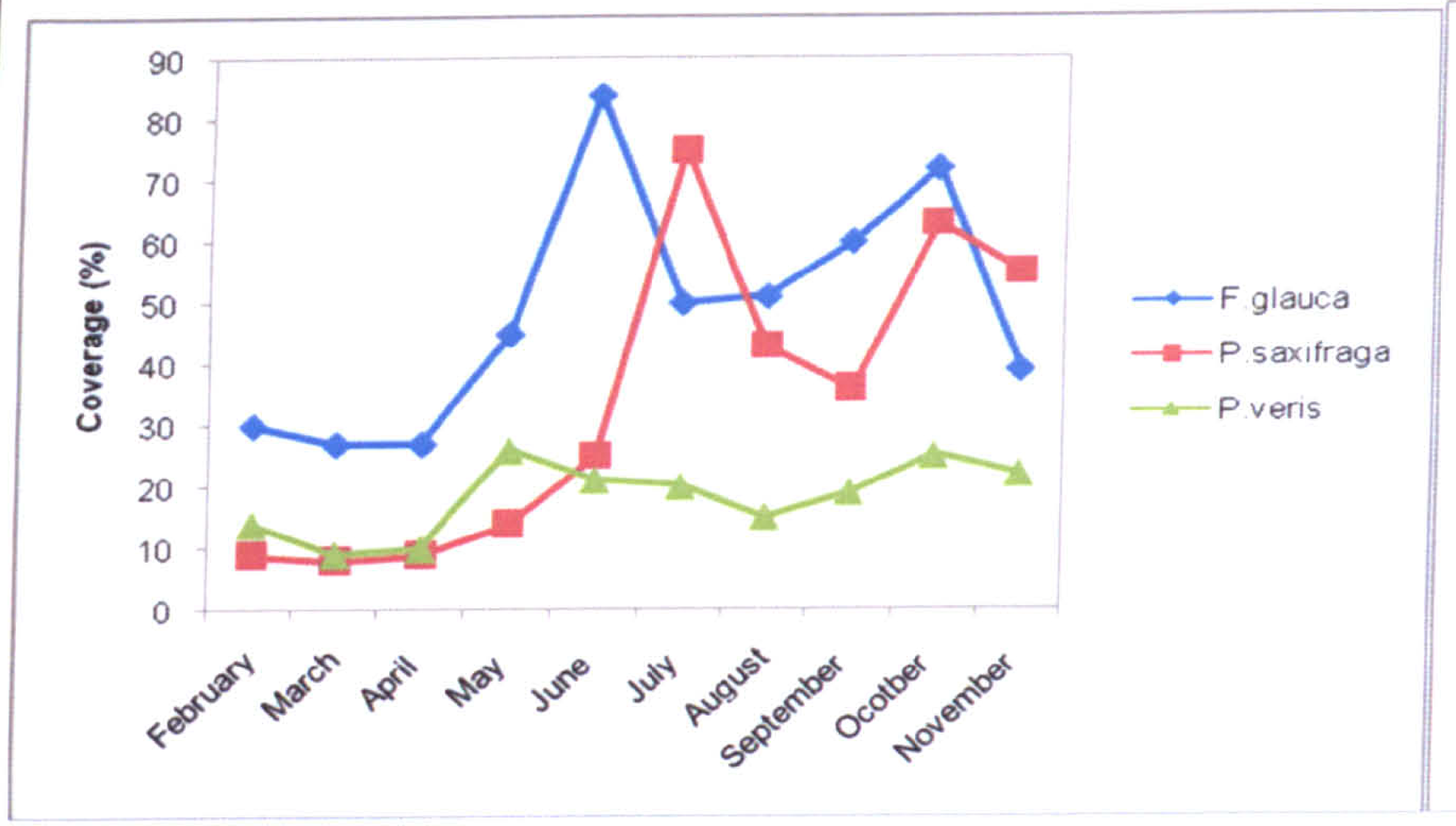


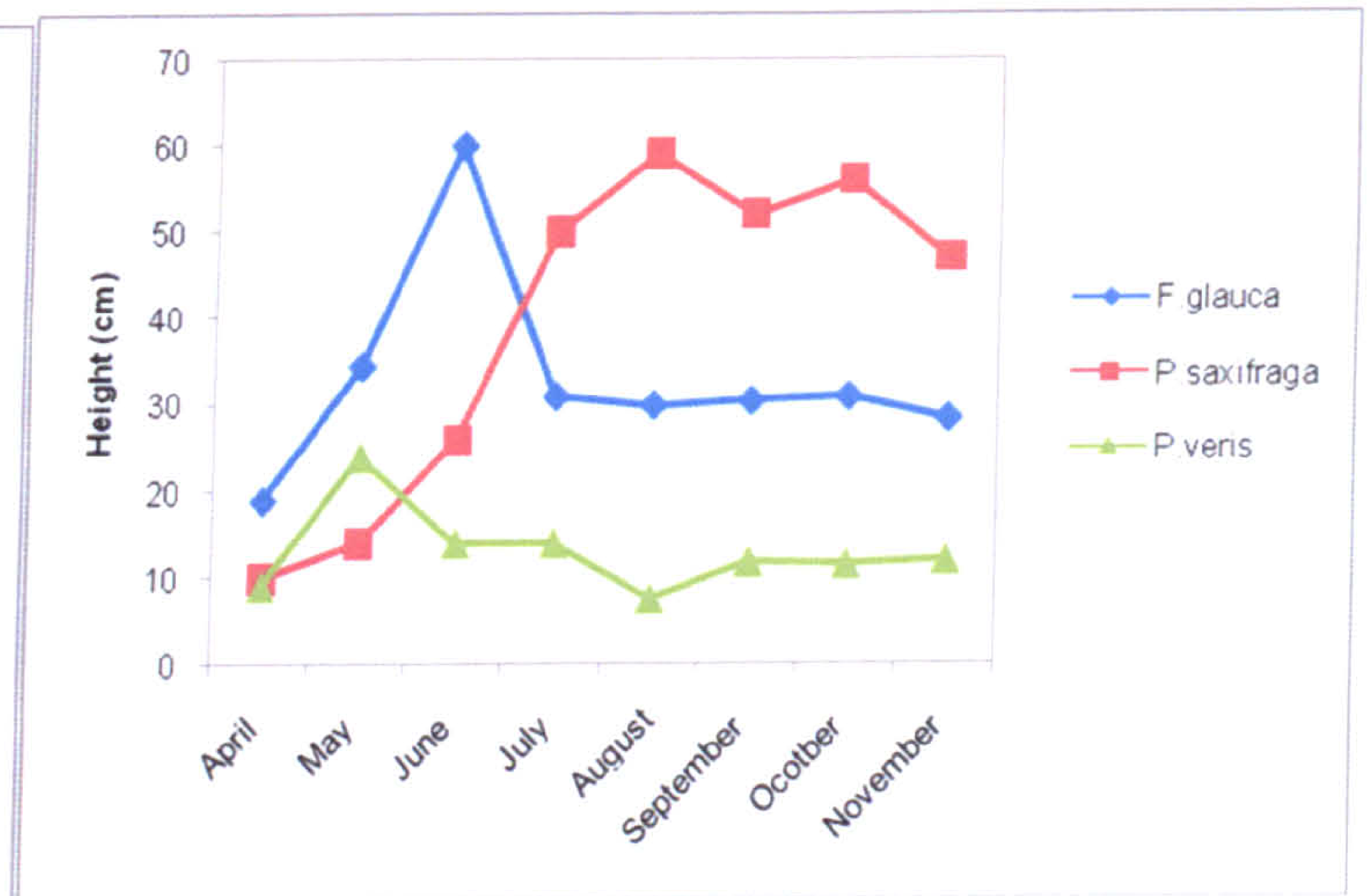
	Growth pattern
S. uniflora	5
S. striatum	3

Quadrat 4(Low diversity, High density, Red, NE)

February	March	April	May	June	July	August	September	October	November

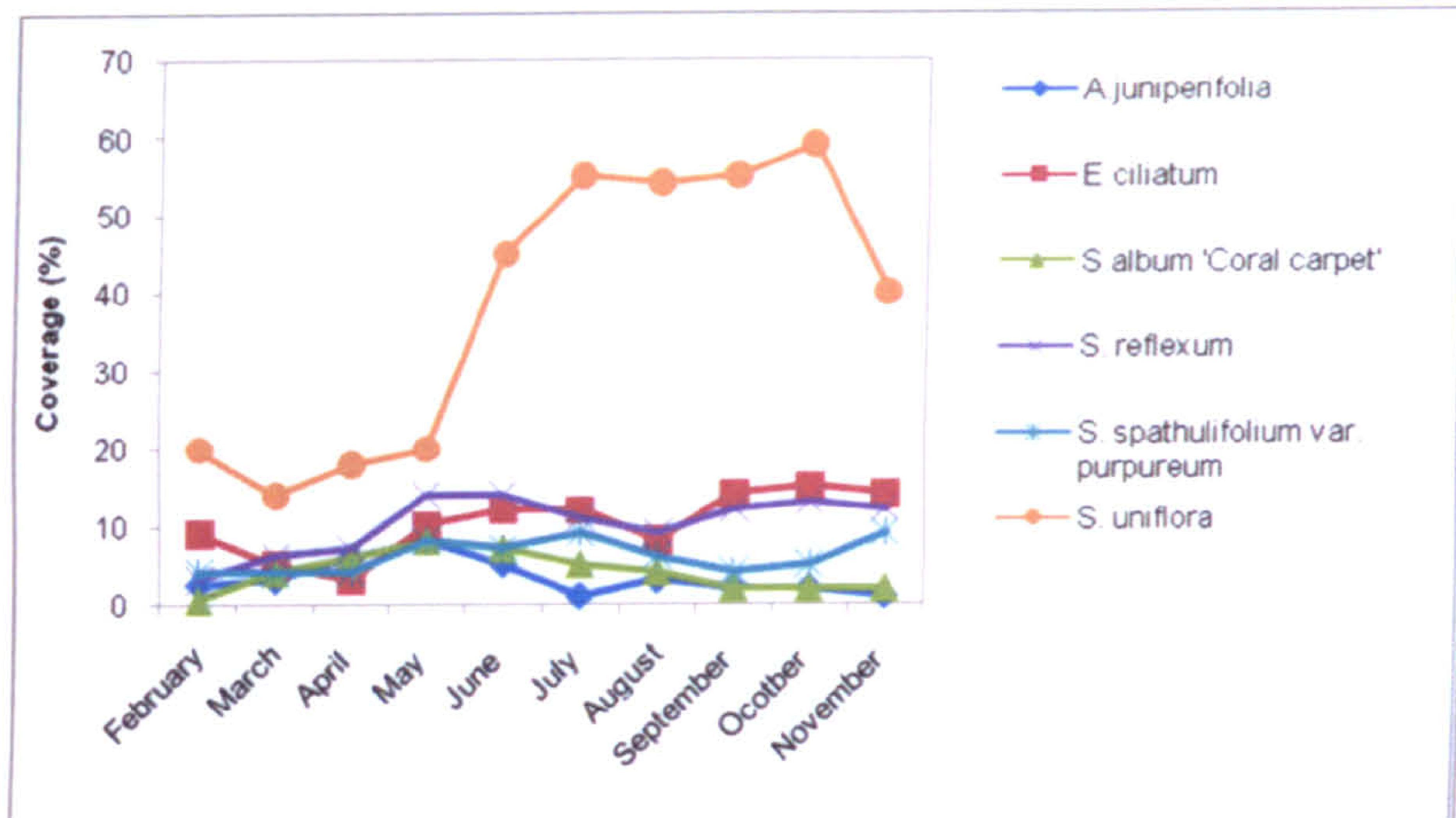
Flower succession										
F. glauca										
P. saxifraga										
P. veris										

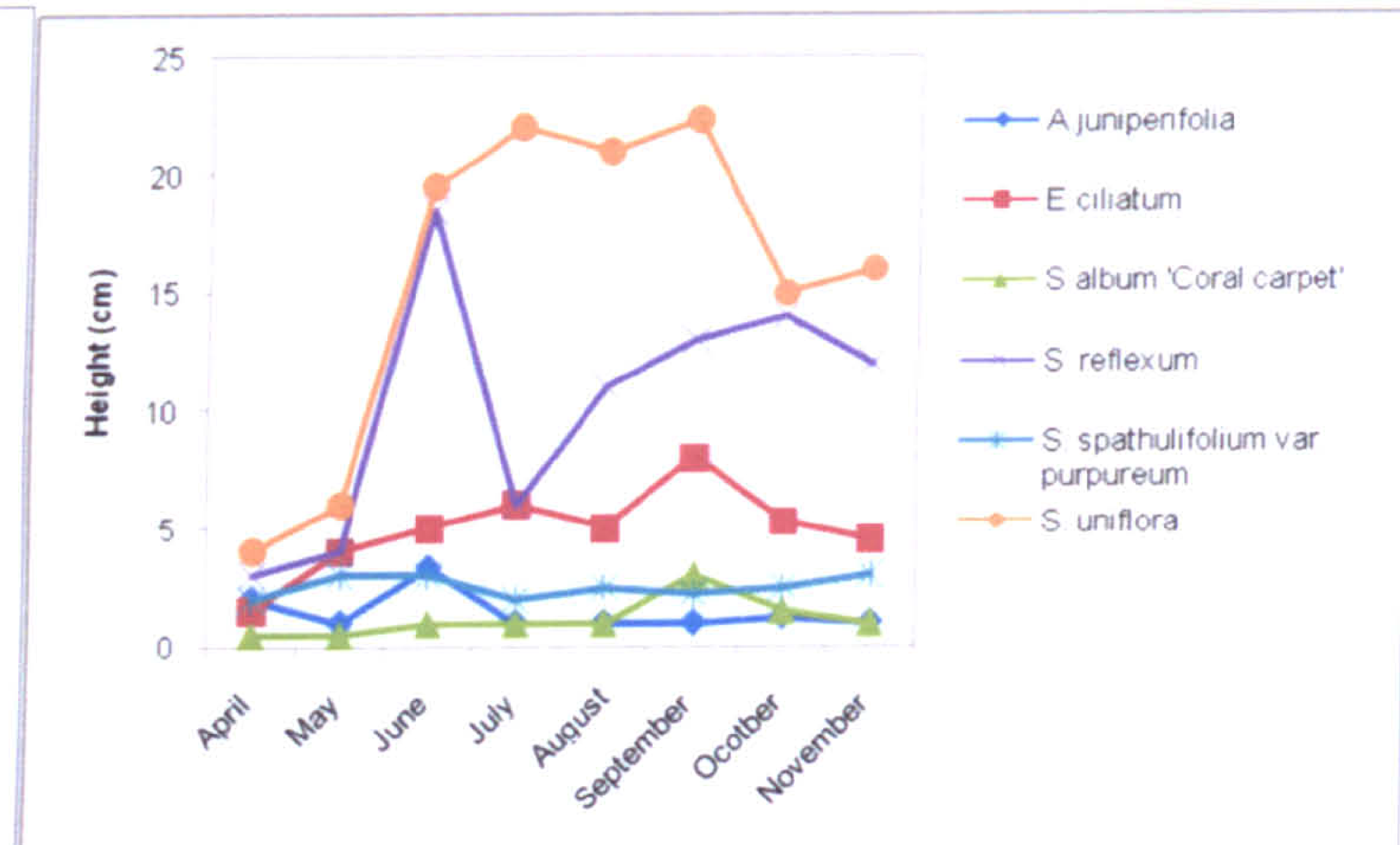




	Growth pattern
F. glauca	3
P. saxifraga	6
P. veris	1

Quadrat 5 (High diversity, Low density, White, NE)



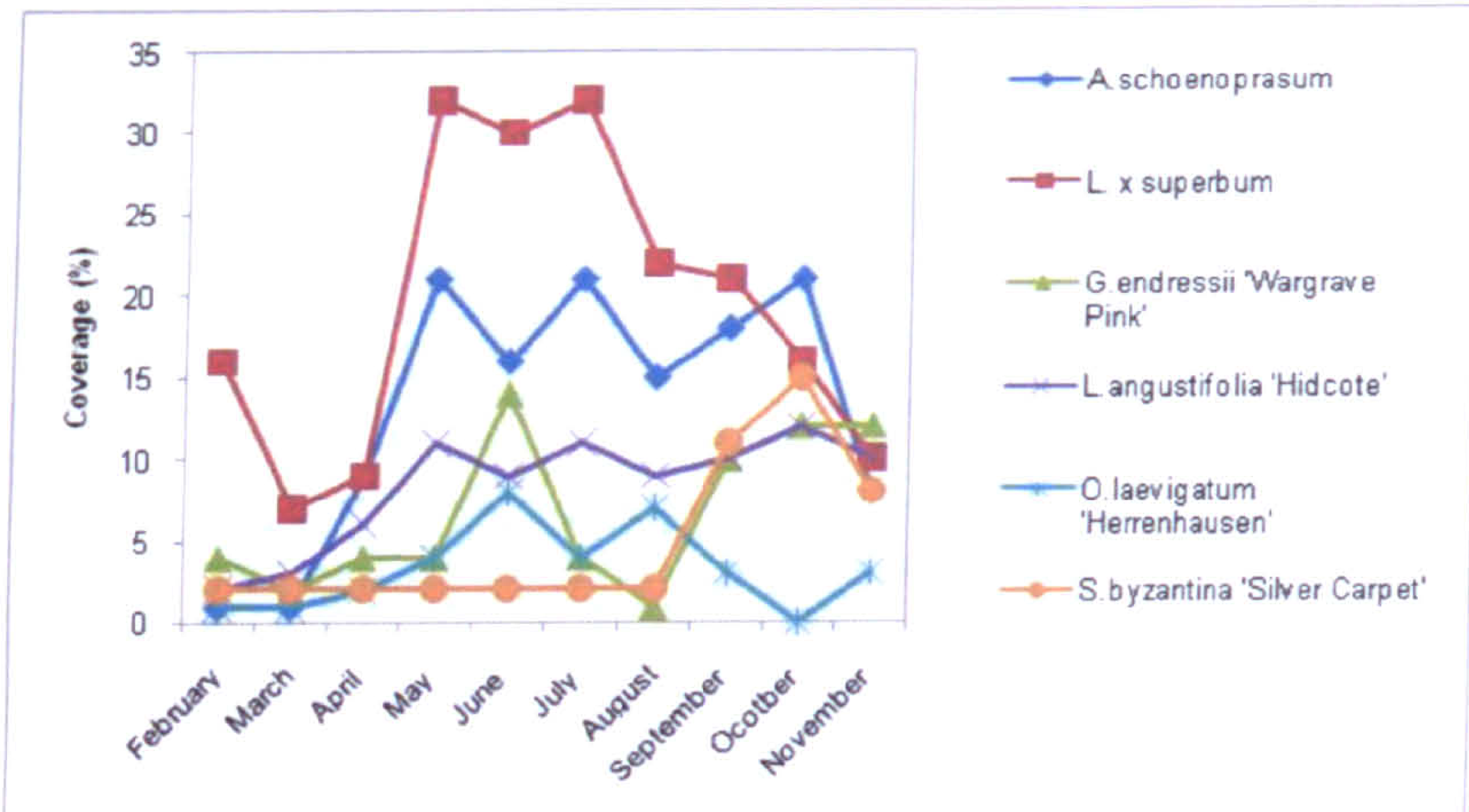


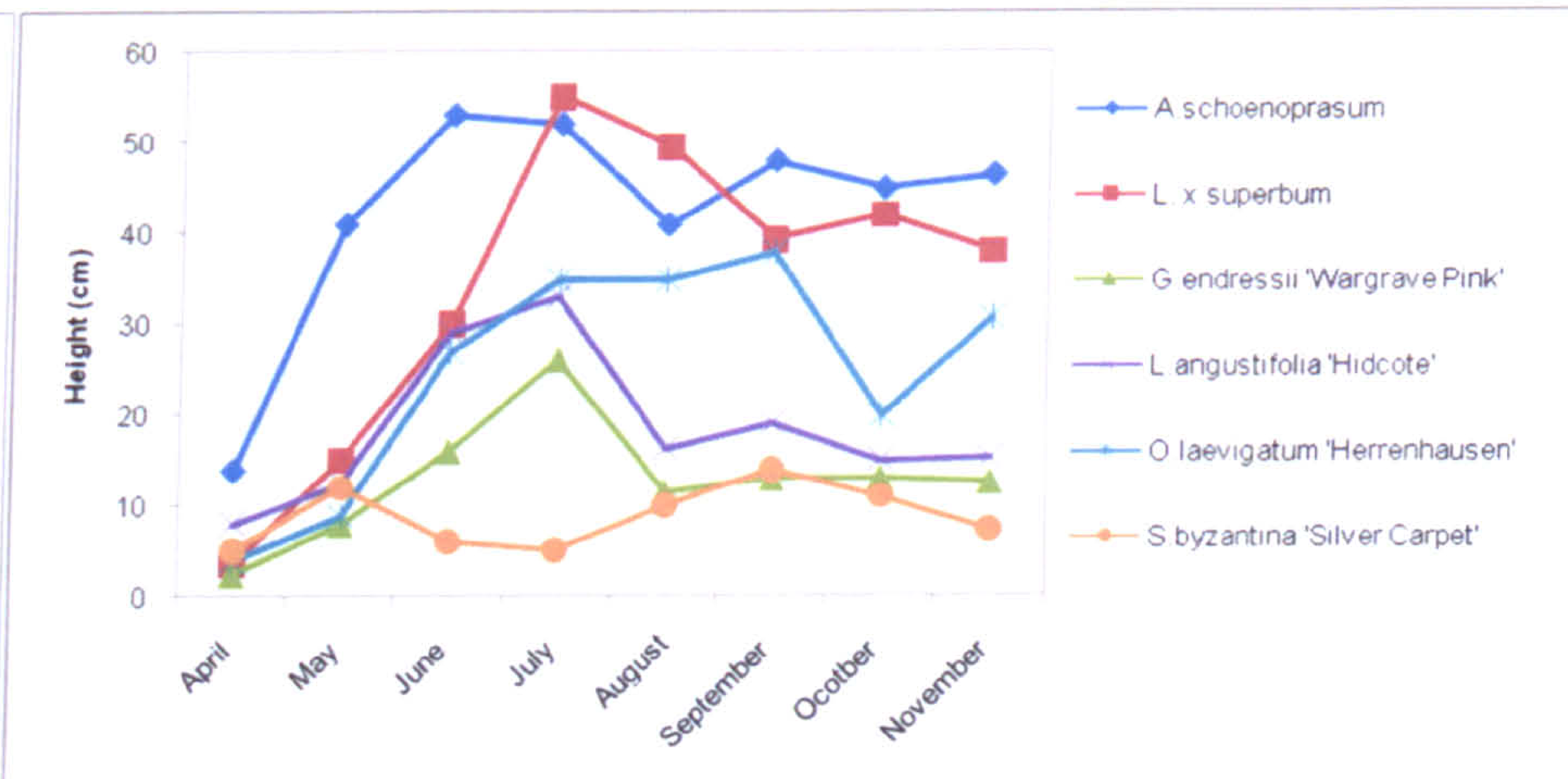
	Growth pattern
A. juniperifolia	1
E. ciliatum	1
S. album 'Coral carpet'	1
S. reflexum	1
S. spathulifolium var. *purpureum*	1
S. uniflora	5

Quadrat 6(High diversity, Low density, Red, NE)

February	March	April	May	June	July	August	September	October	November

Flower succession	April	May	June	July	August	September	October	November
A. schoenoprasum								
L. x superbum								
G. endressii 'Wargrave Pink'								
L. angustifolia 'Hidcote'								
O. laevigatum 'Herrenhausen'								
S. byzantina 'Silver Carpet'	No flower							



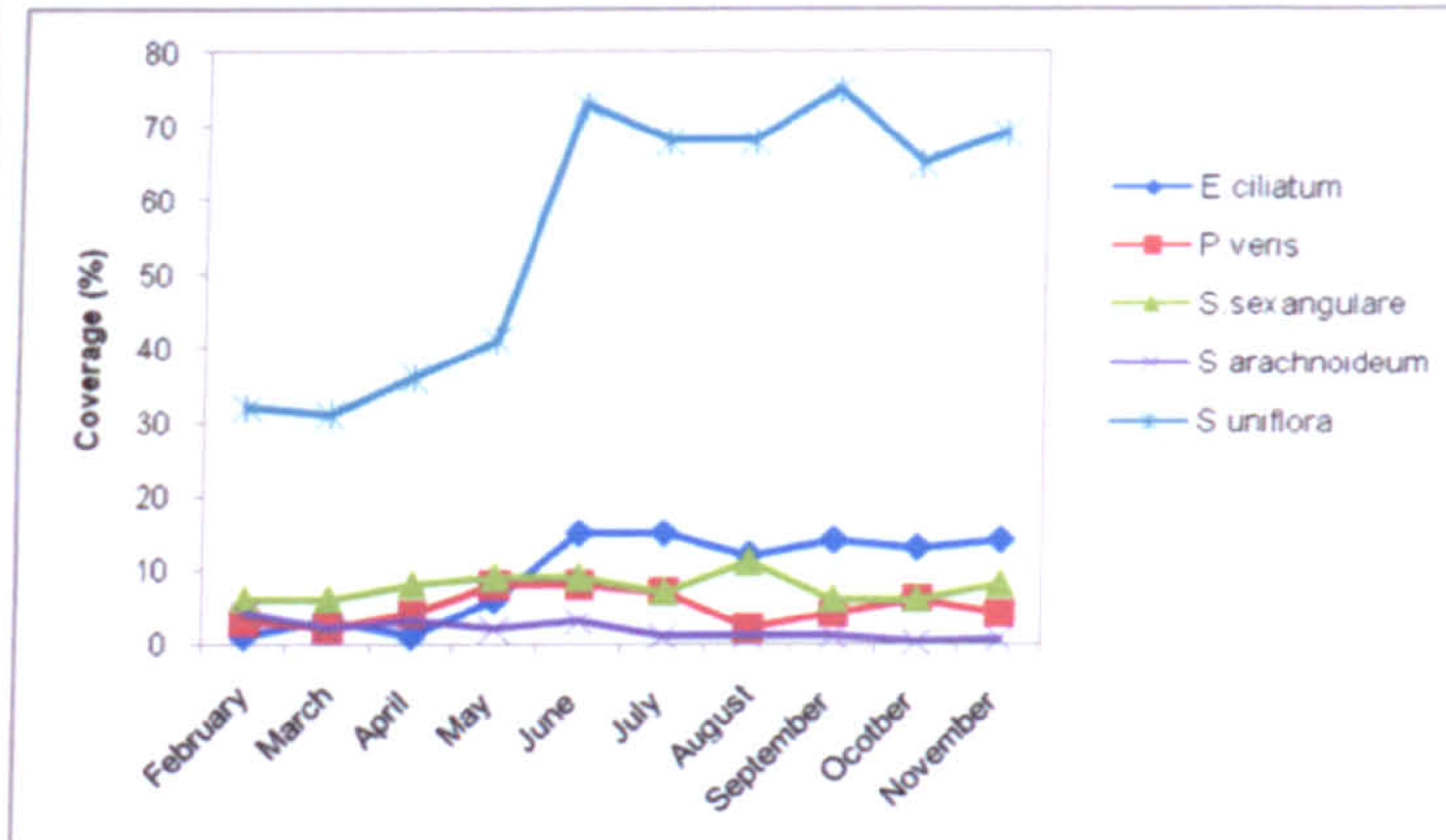


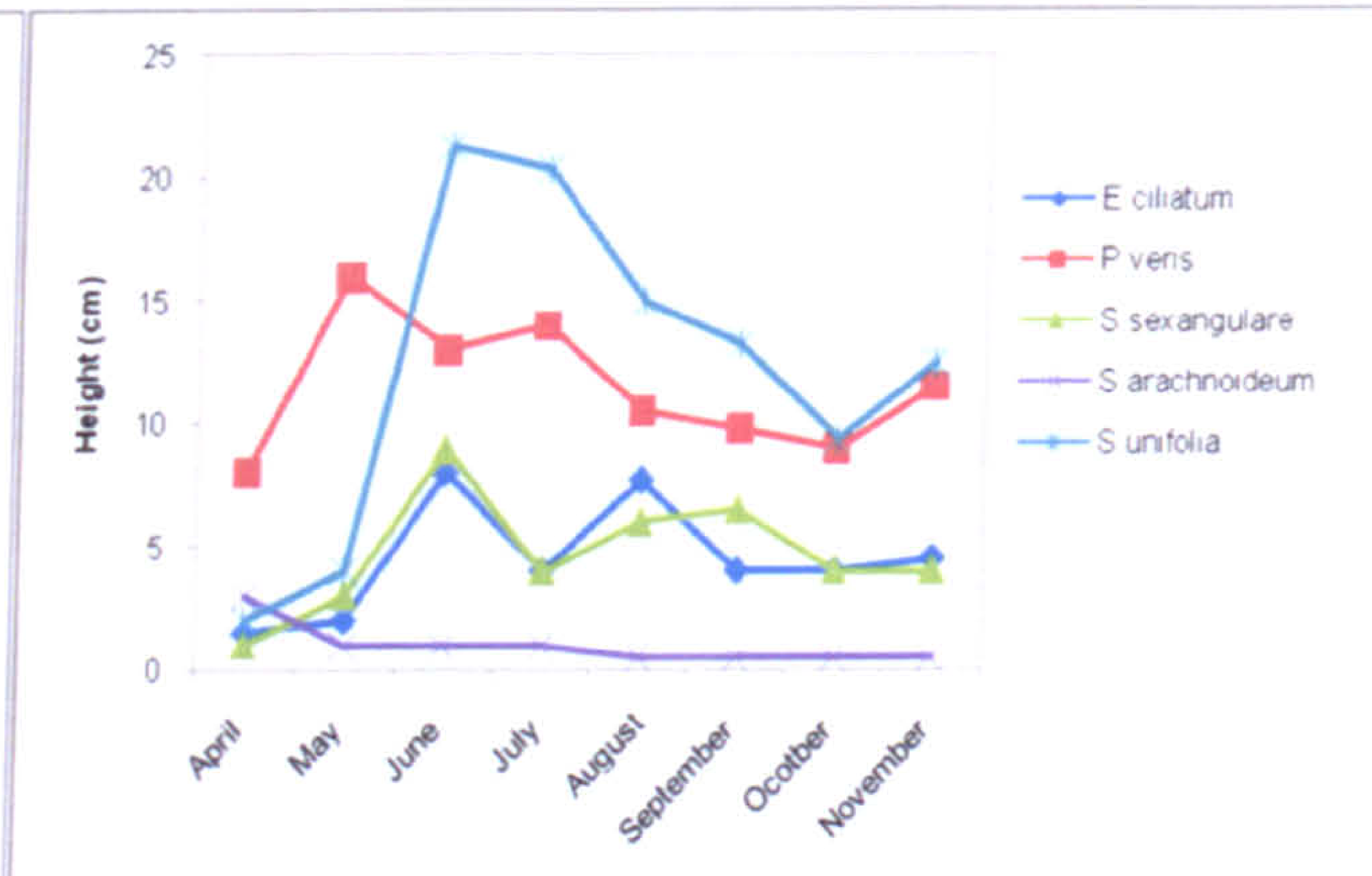
	Growth pattern
A. schoenoprasum	5
L. x superbum	4
G .endressii 'Wargrave Pink'	3
L. angustifolia 'Hidcote'	2
O. laevigatum 'Herrenhausen'	4
S. byzantina 'Silver Carpet'	5

Quadrat 7(High diversity, High density, White, NE)

February	March	April	May	June	July	August	September	October	November

Flower succession										
E. ciliatum										
P. veris										
S. sexangulare										
S. arachnoideum	No flower									
S. uniflora										



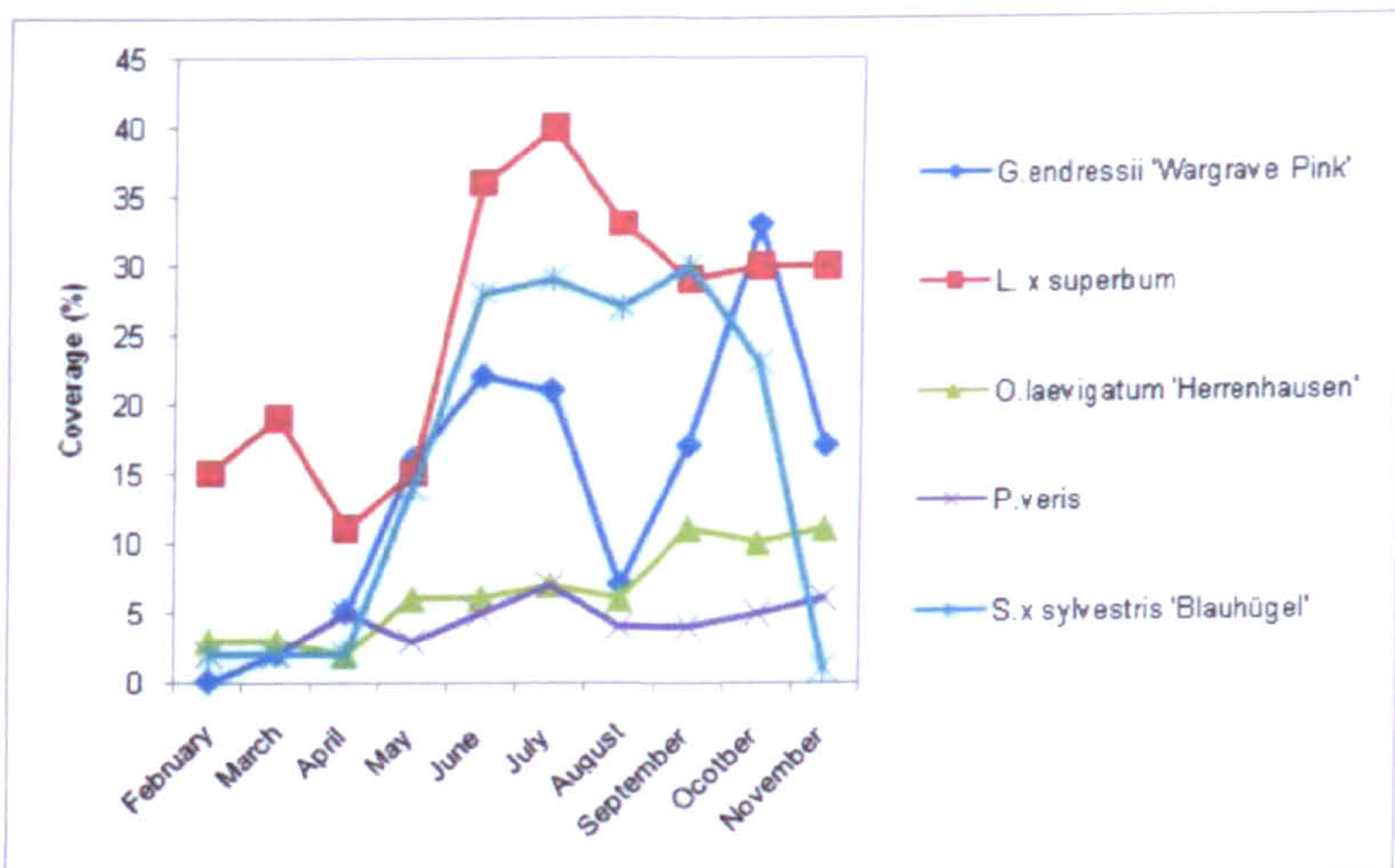


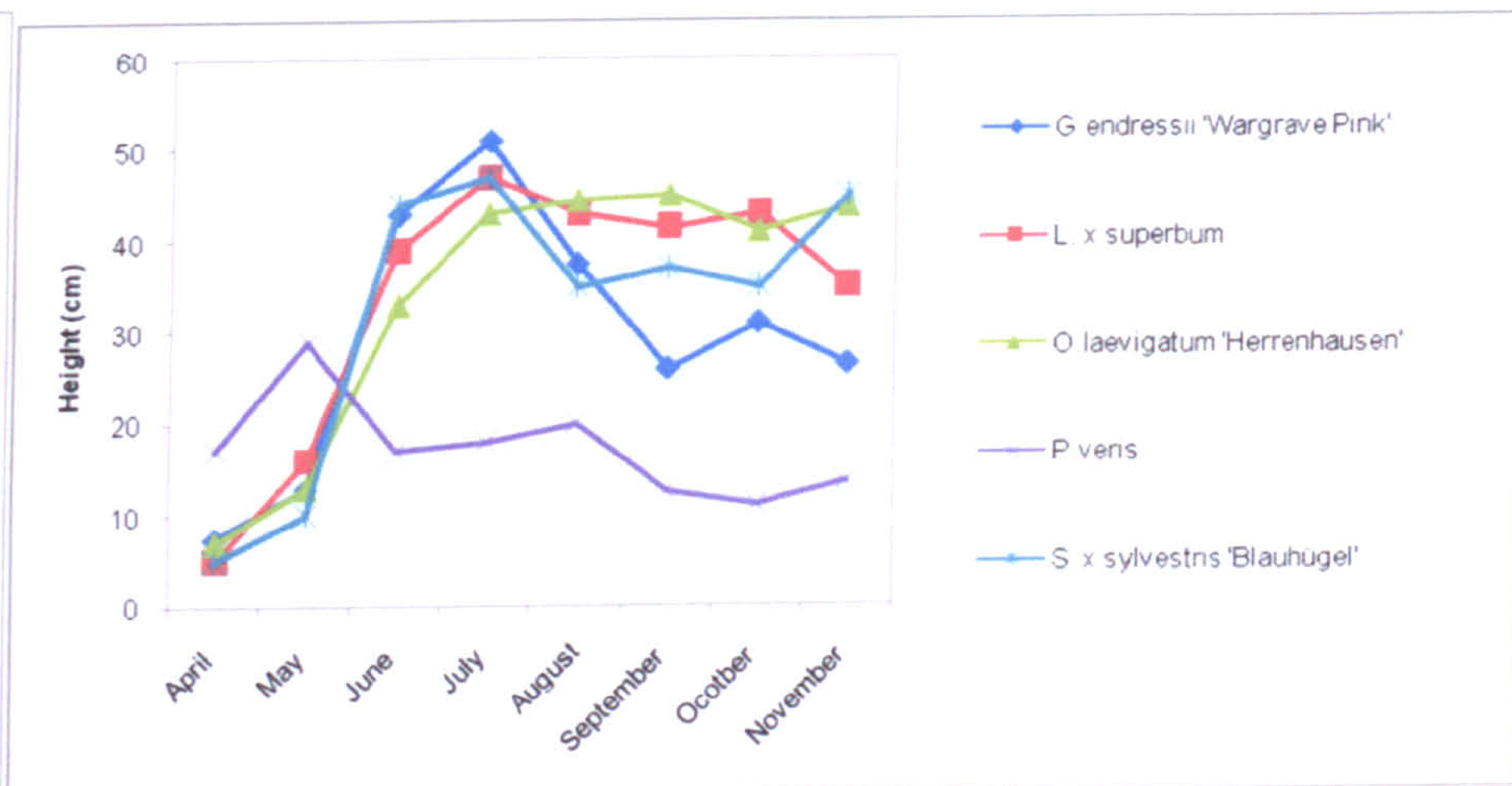
	Growth pattern
E. ciliatum	1
P. veris	1
S. sexangulare	1
S. arachnoideum	1
S. uniflora	5

Quadrat 8(High diversity, High density, Red, NE)

February	March	April	May	June	July	August	September	October	November

Flower succession
G. endressii 'Wargrave Pink'
L. x superbum
O. laevigatum 'Herrenhausen'
P. veris
S. x sylvestris 'Blauhügel'



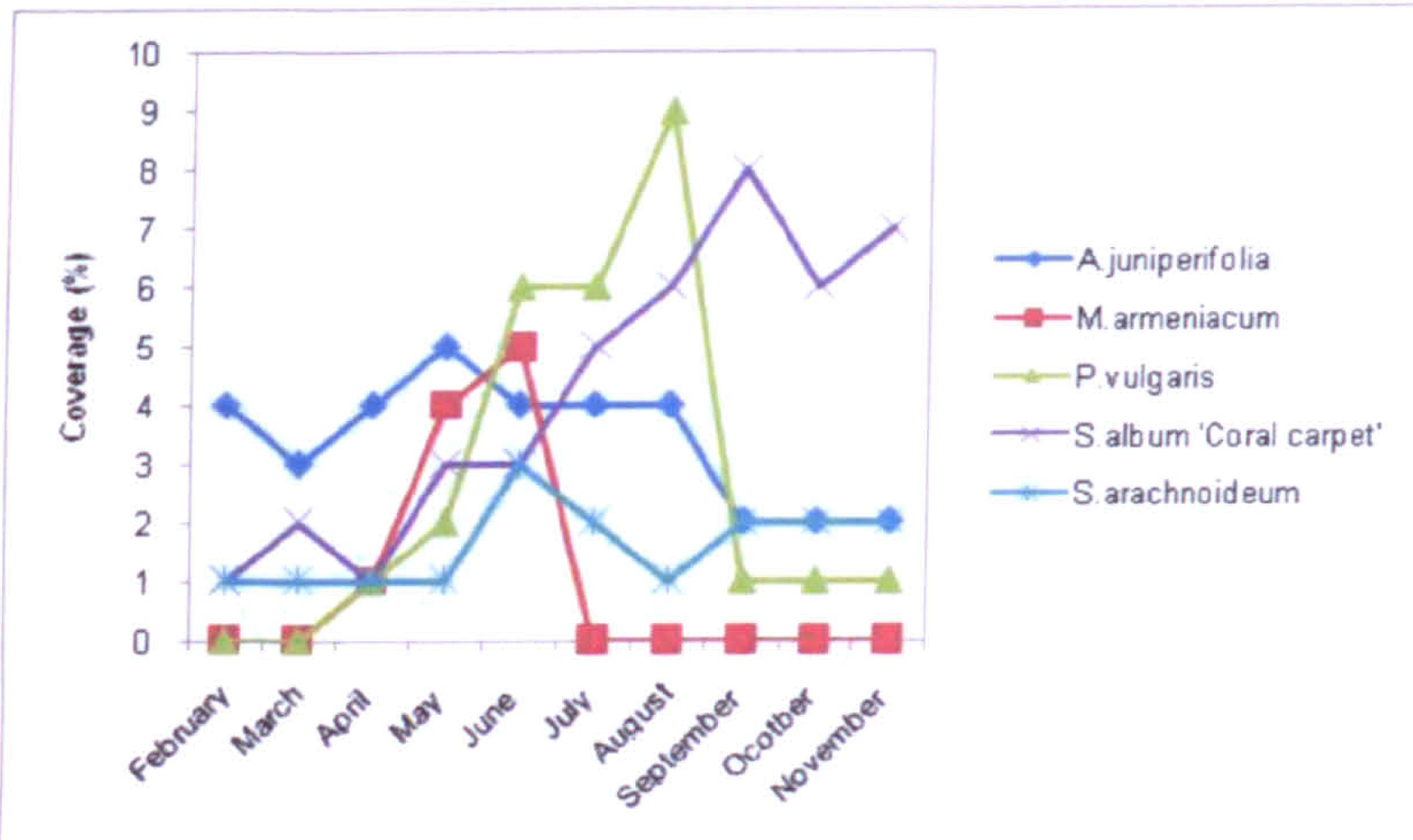


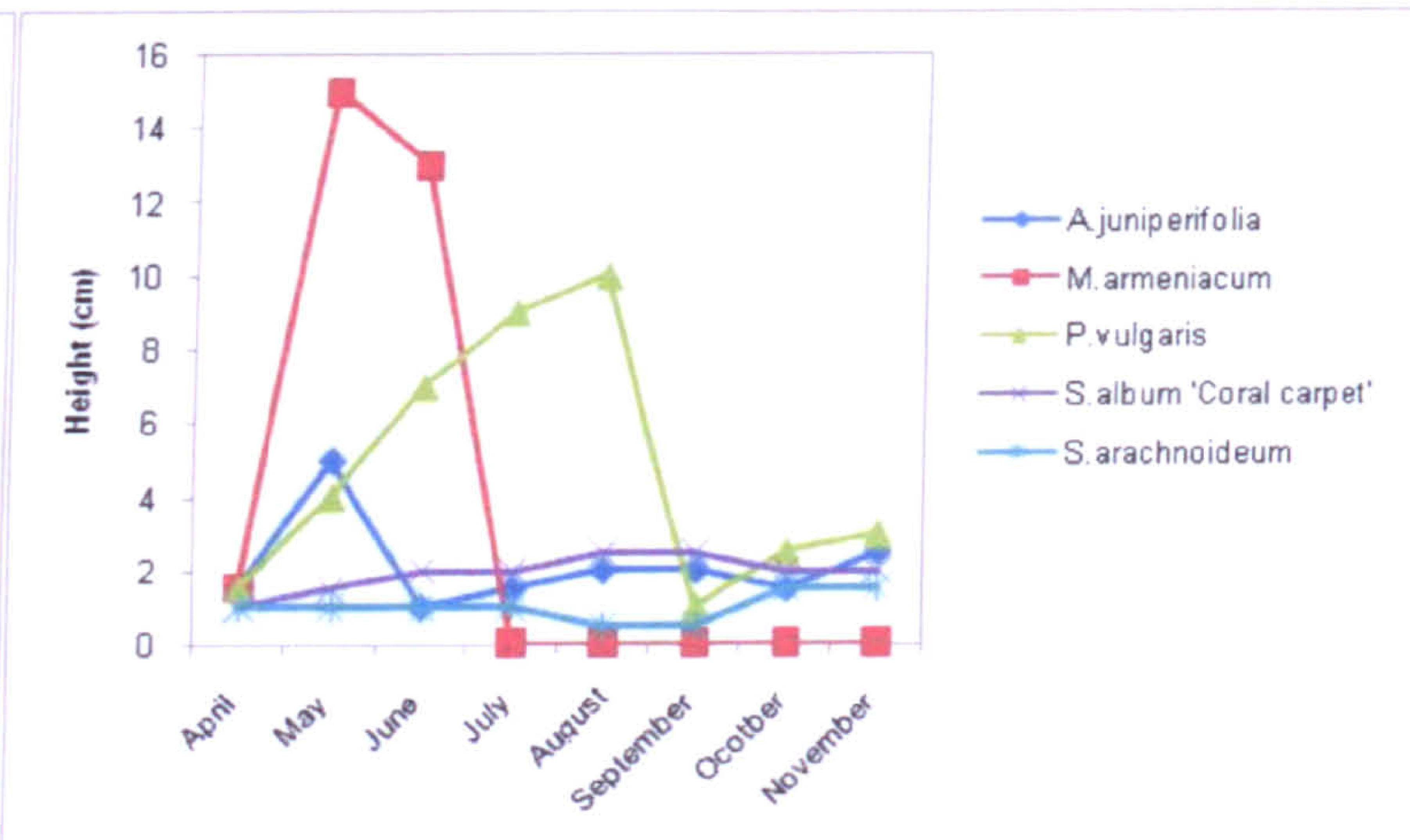
	Growth pattern
G. endressii 'Wargrave Pink'	3
L. x superbum	4
O. laevigatum 'Herrenhausen'	4
P. veris	1
S. x sylvestris 'Blauhügel'	4

Quadrat 9(Low diversity, Low density, White, NW)

February	March	April	May	June	July	August	September	October	November

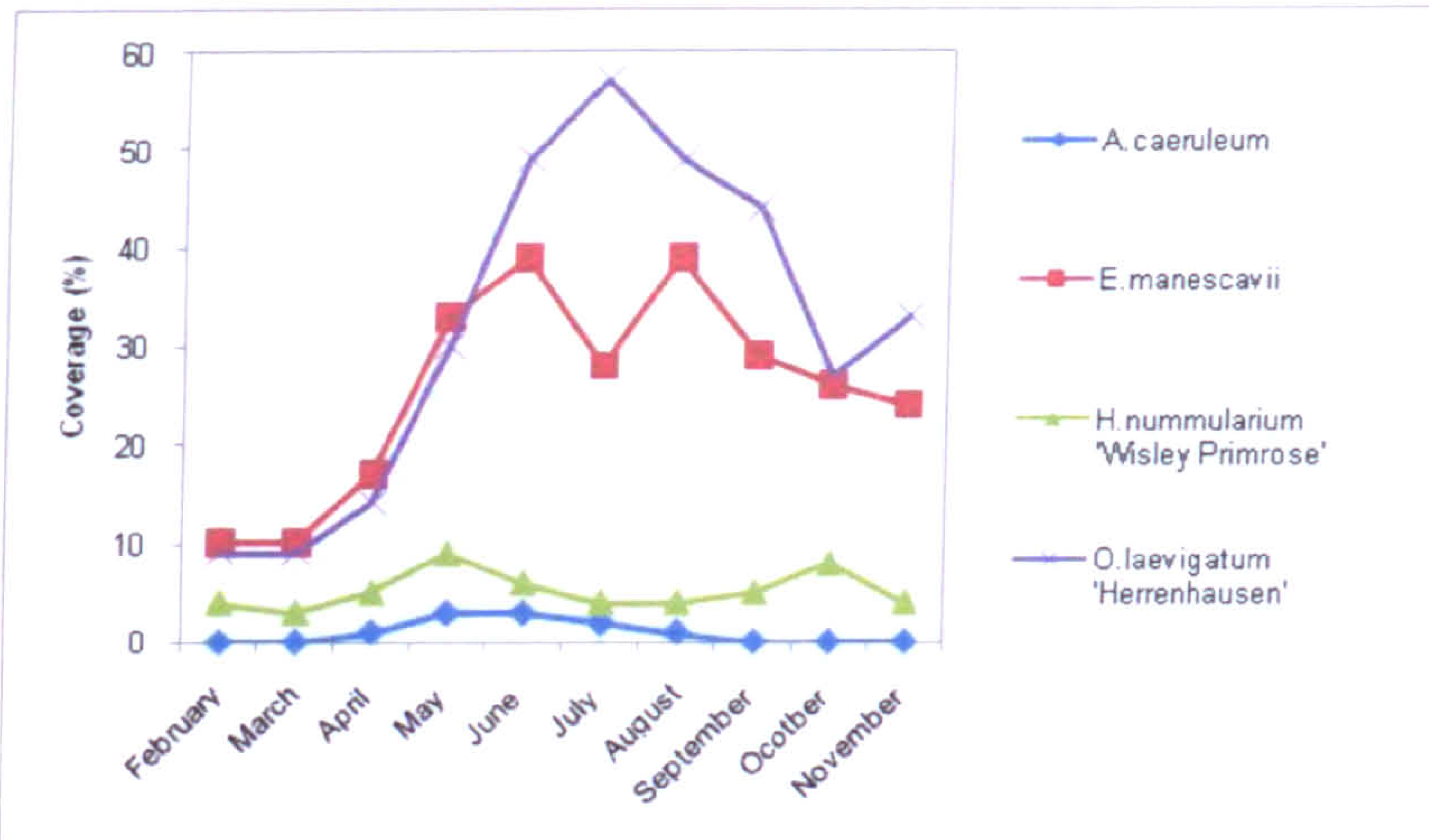
Flower succession									
A .juniperifolia									
M .armeniacum									
P. vulgaris	No flower								
S. album 'Coral carpet'									
S. arachnoideum									

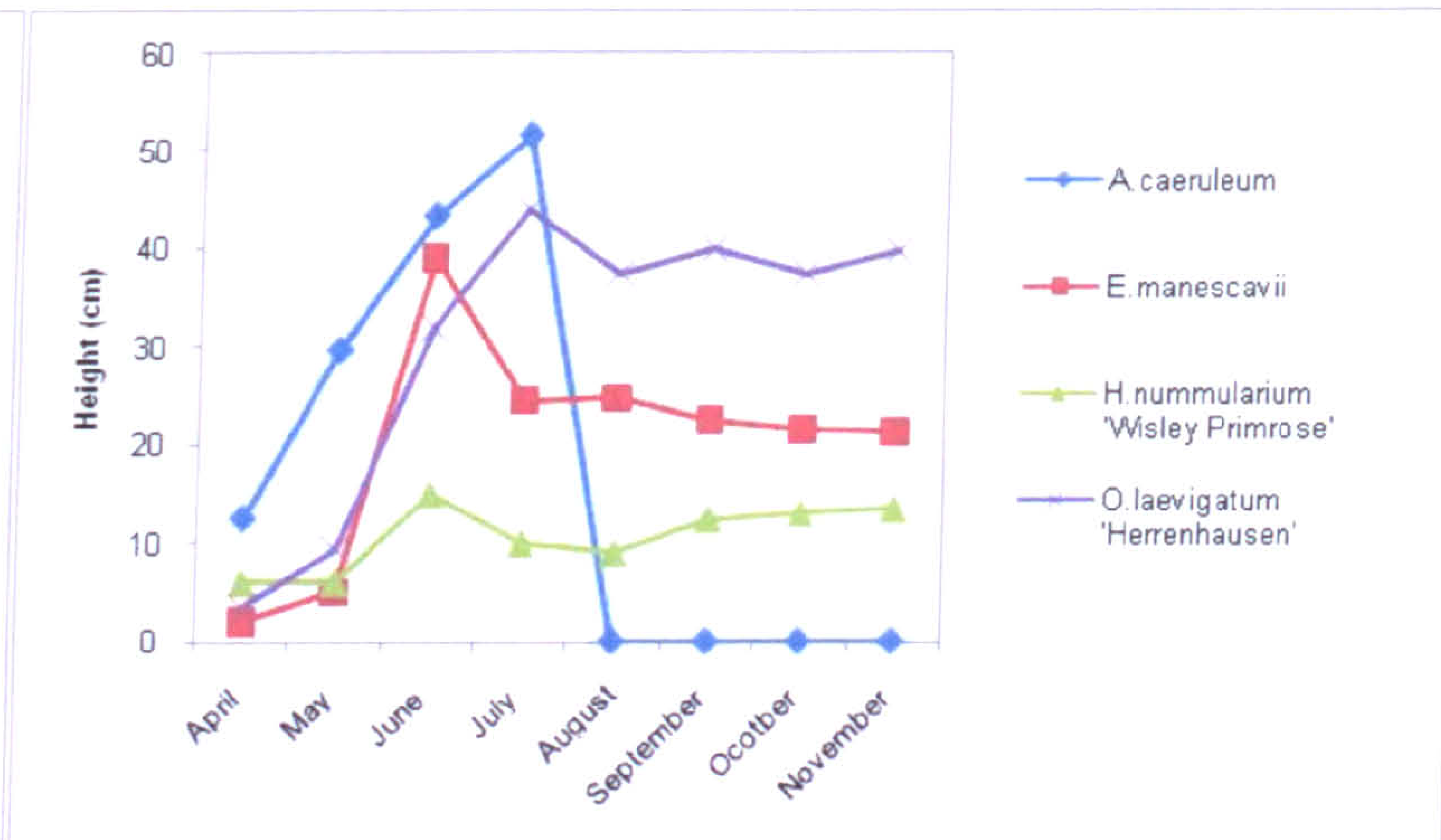




	Growth pattern
A .juniperifolia	1
M .armeniacum	2
P. vulgaris	3
S. album 'Coral carpet'	1
S. arachnoideum	1

Quadrat 10 (Low diversity, Low density, Red, NW)

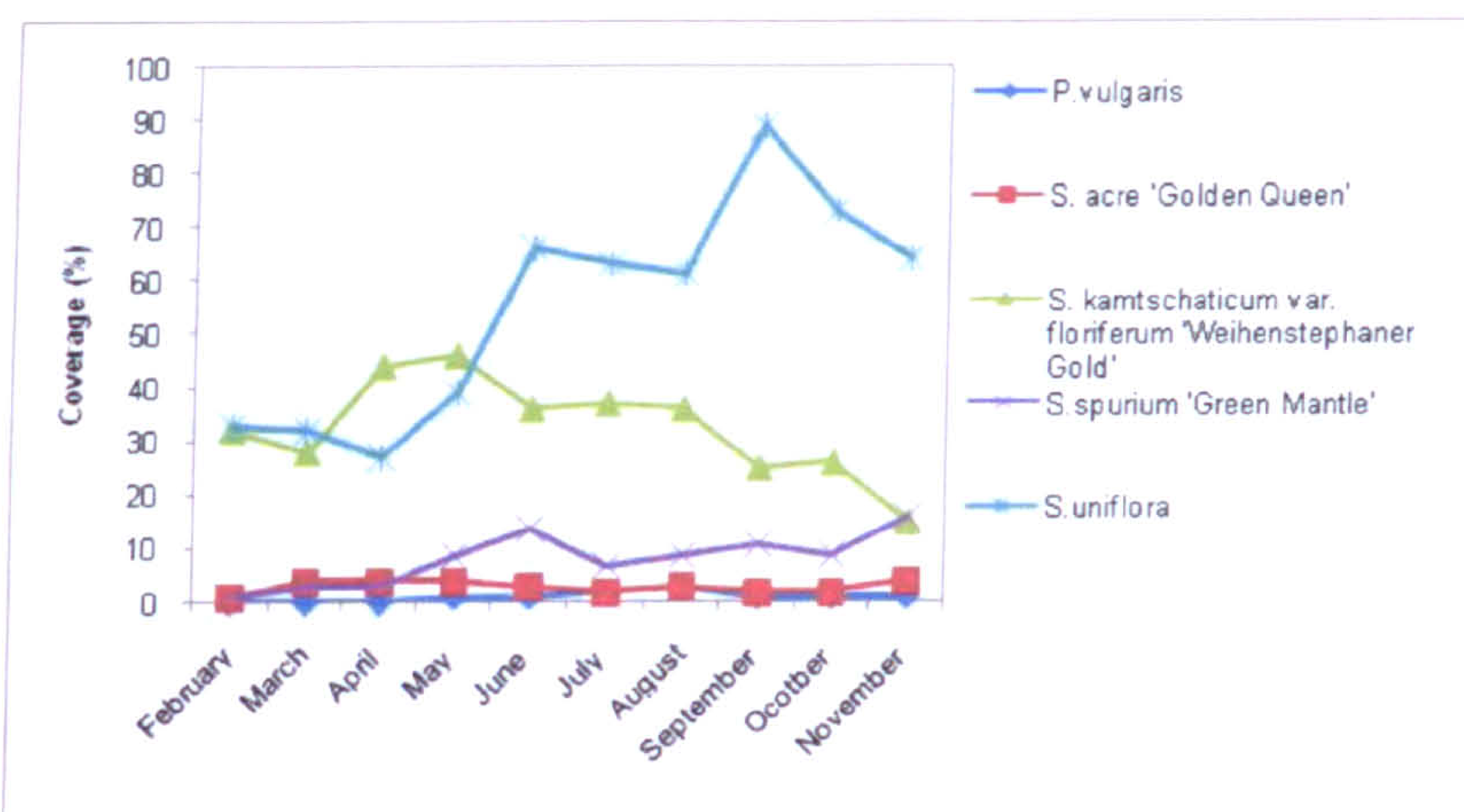


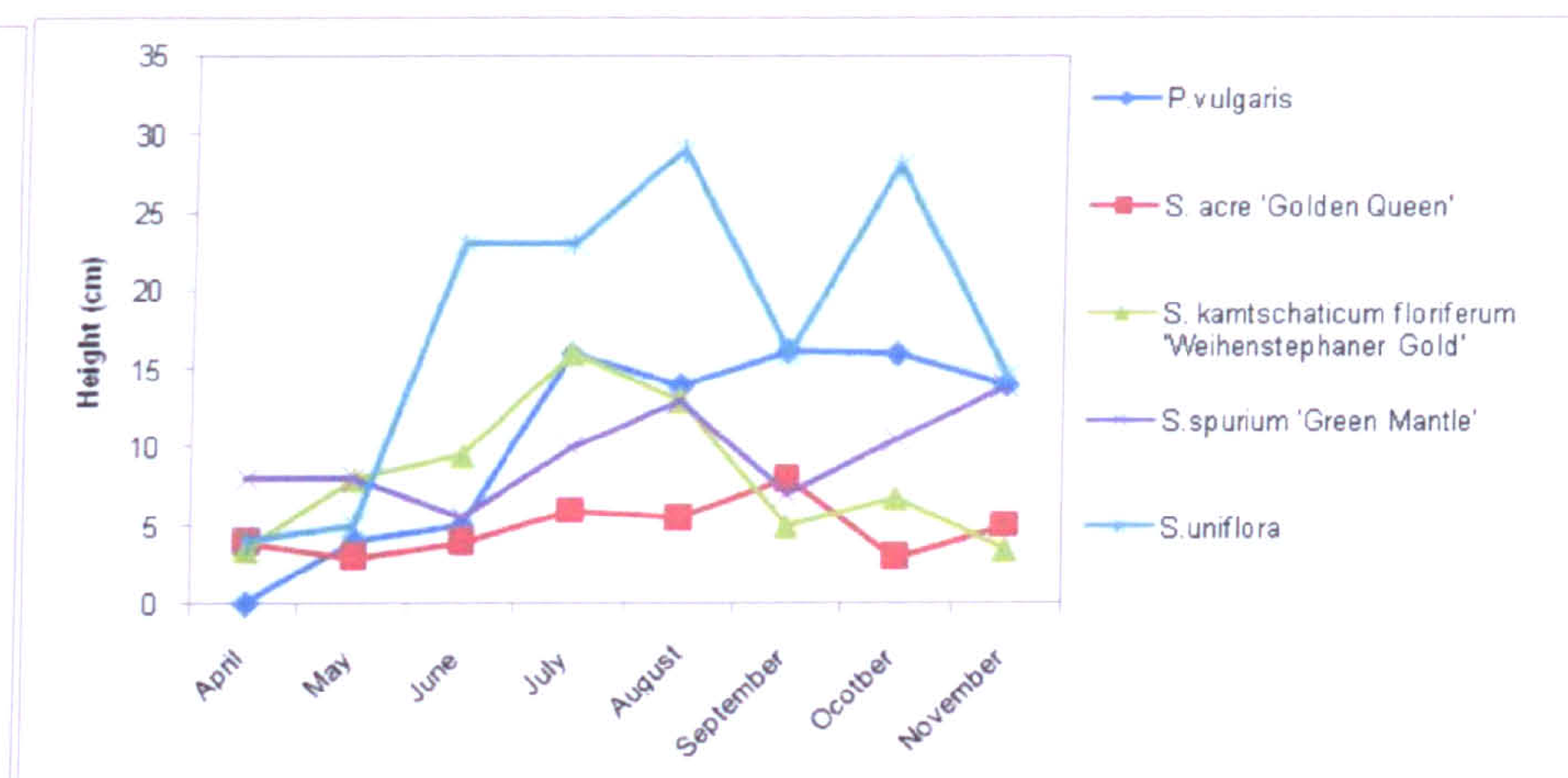


	Growth pattern
A. caeruleum	3
E. manescavii	3
H. nummularium 'Wisley Primrose'	1
O. laevigatum 'Herrenhausen'	4

Quadrat 11(Low diversity, High density, White, NW)

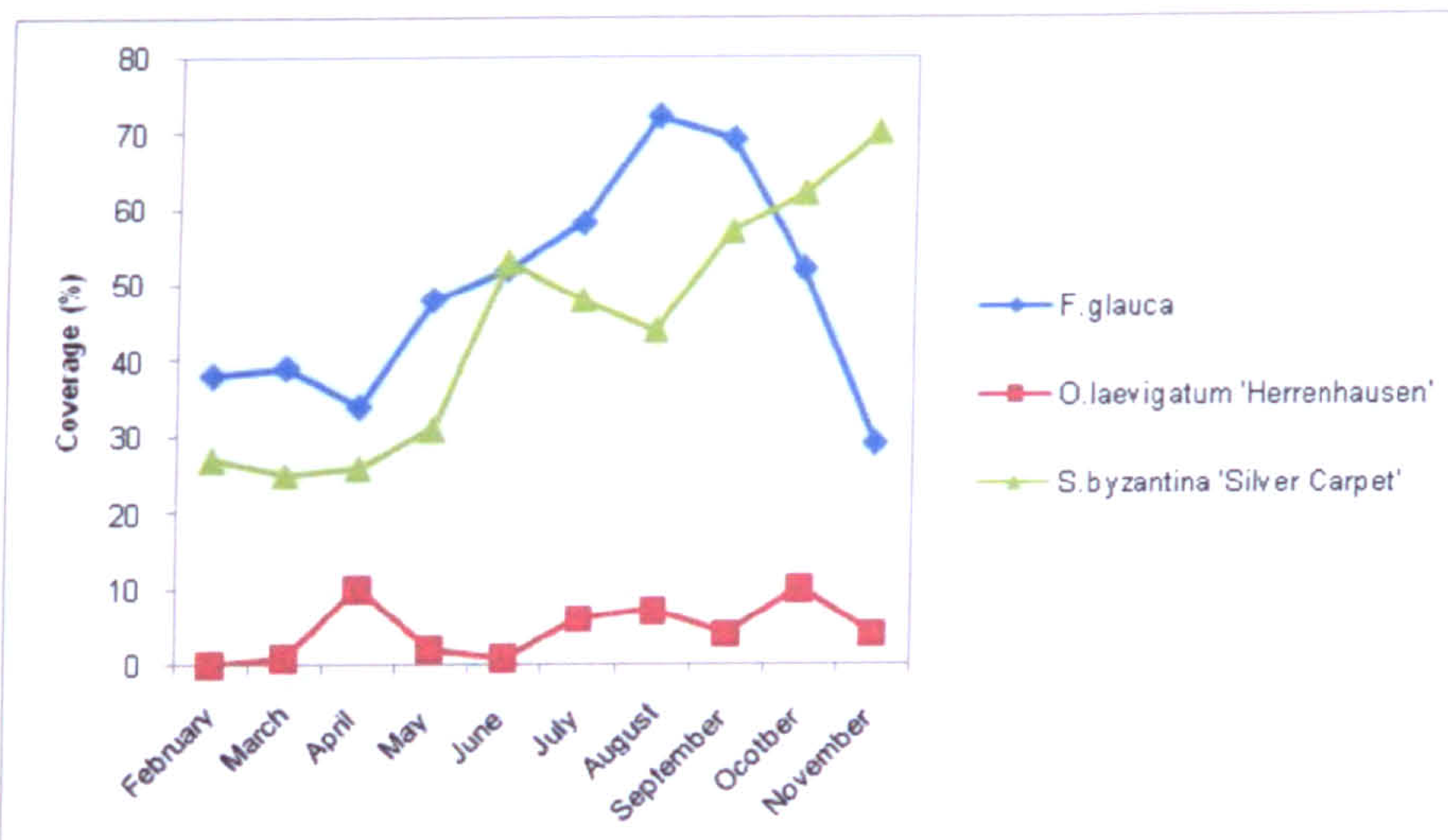
February	March	April	May	June	July	August	September	October	November
						Missing			
Flower succession									
P. vulgaris		No flower							
S. acre 'Golden Queen'		No flower							
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'									
S. spurium 'Green Mantle'		No flower							
S. uniflora									

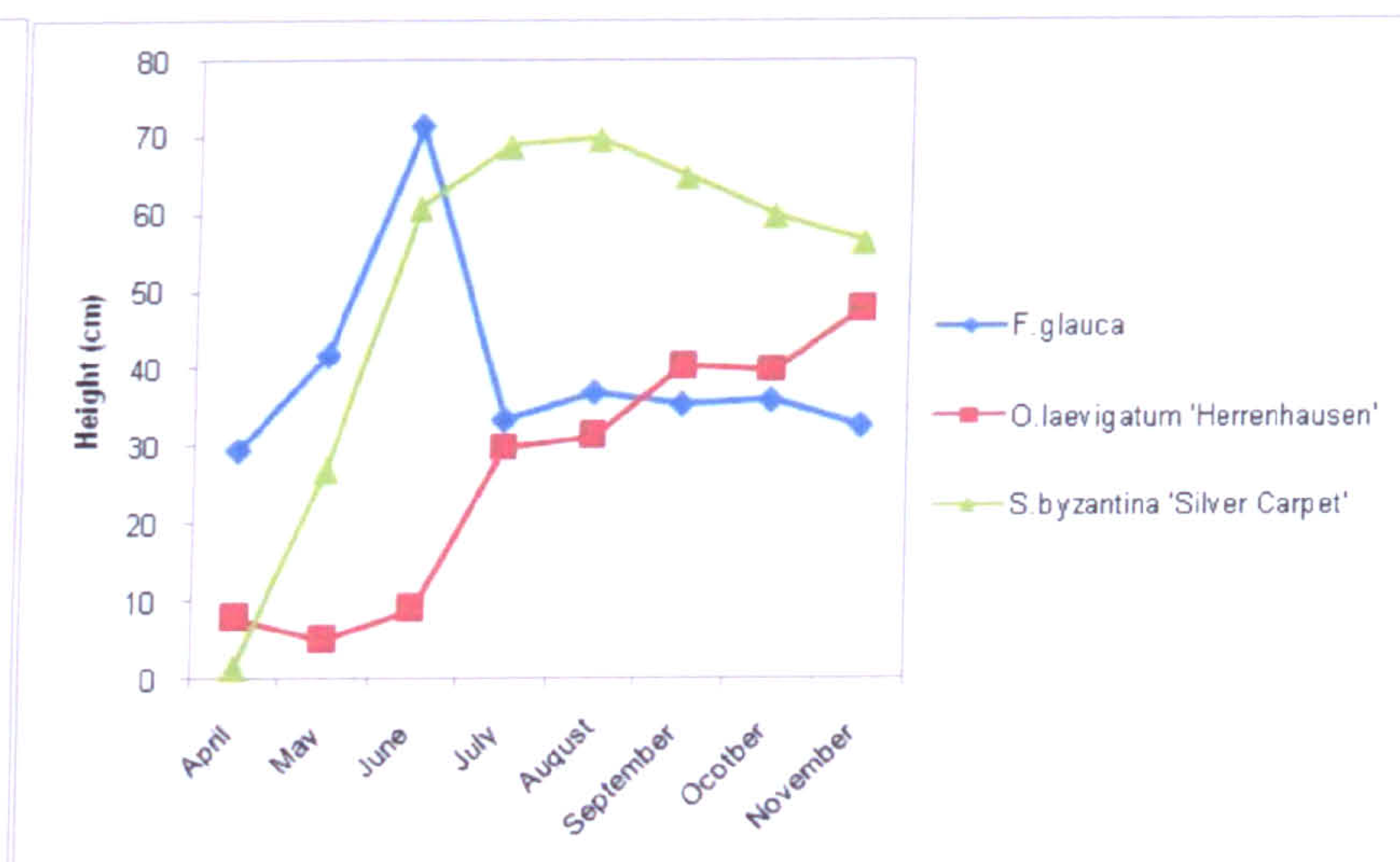




	Growth pattern
P. vulgaris	3
S. acre 'Golden Queen'	1
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'	1
S. spurium 'Green Mantle'	1
S. uniflora	5

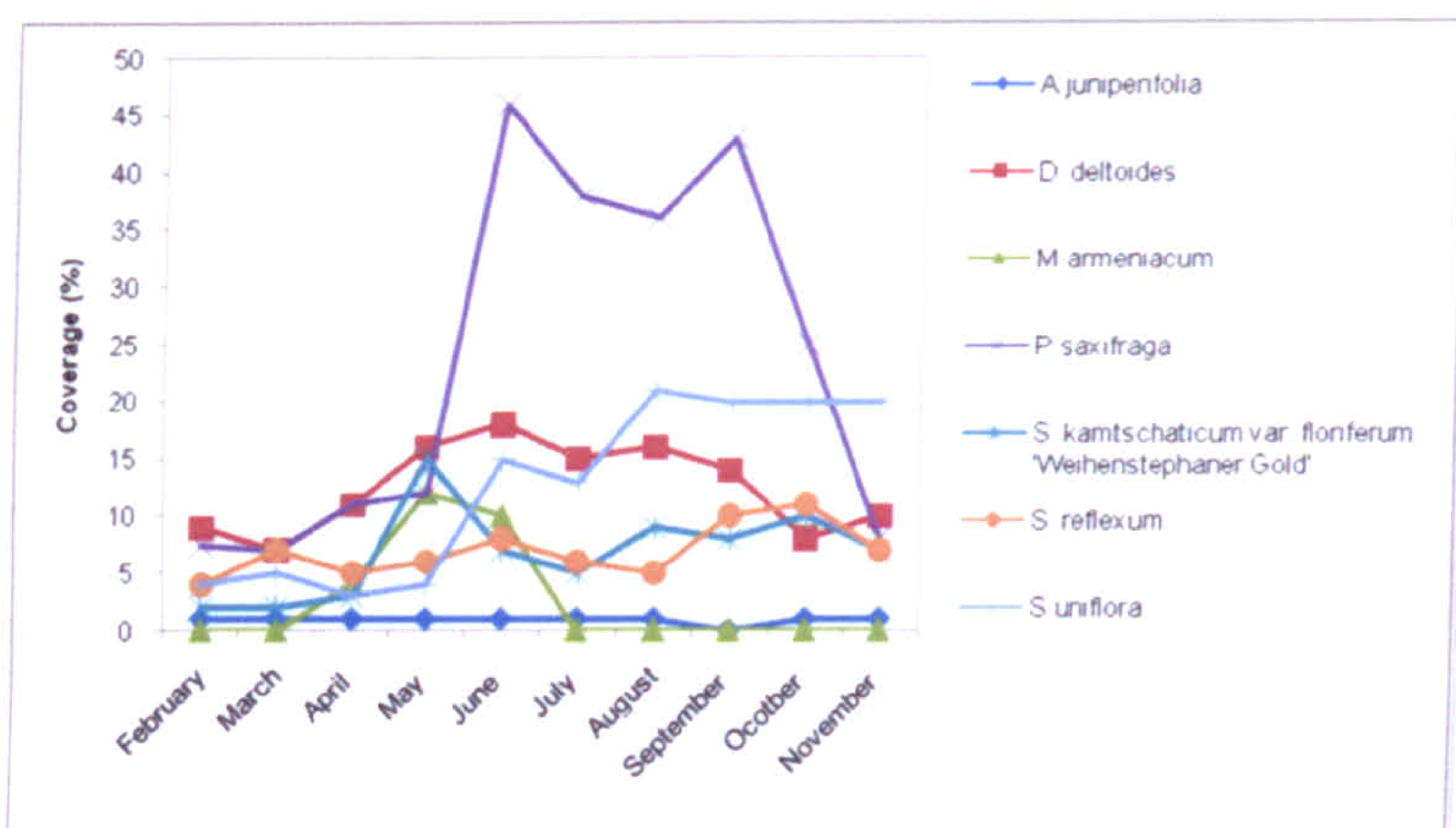
Quadrat 12(Low diversity, High density, Red, NW)

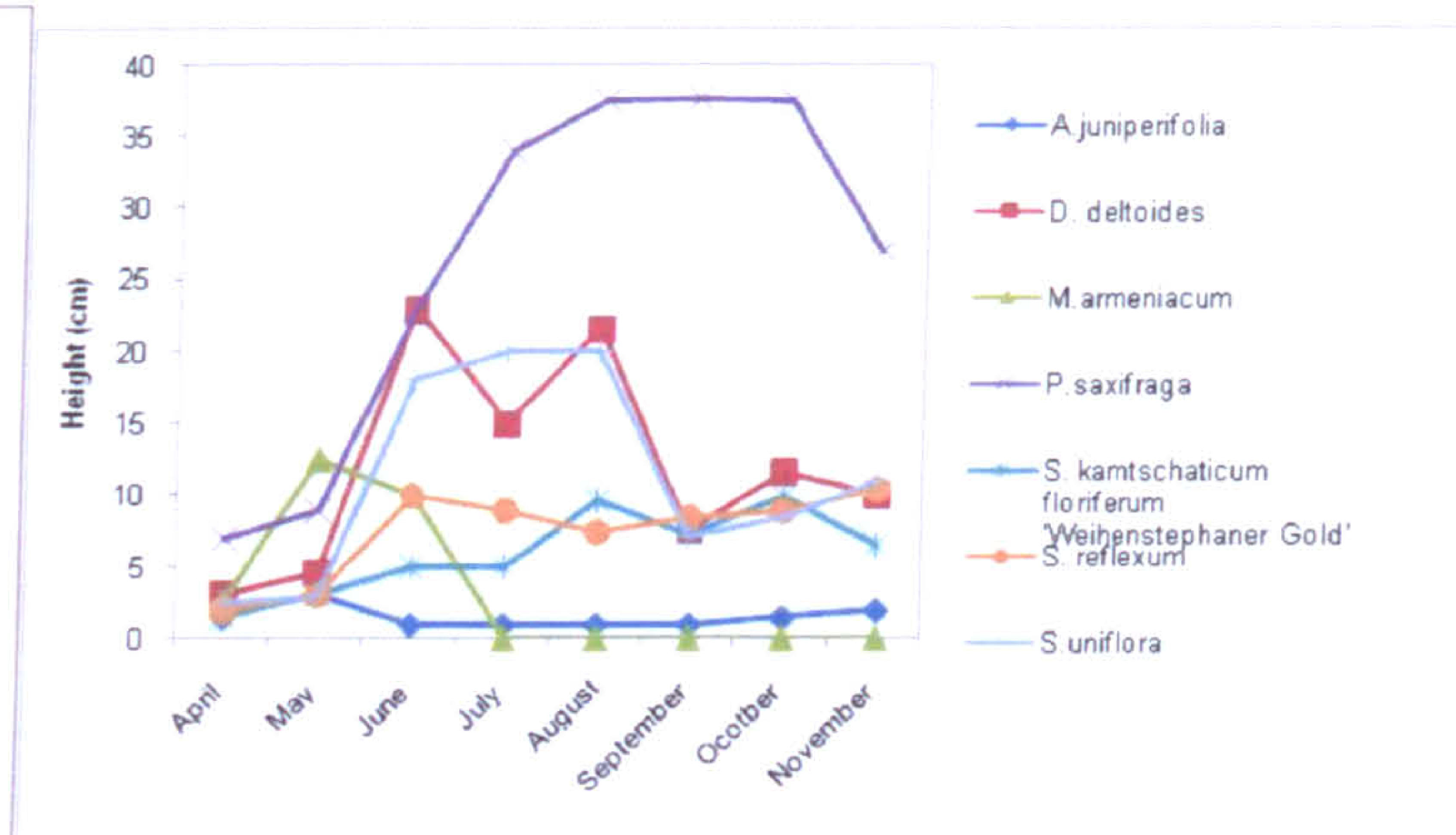




	Growth pattern
F. glauca	3
O. laevigatum 'Herrenhausen'	4
S. byzantina 'Silver Carpet'	5

Quadrat 13(High diversity, Low density, White, NW)

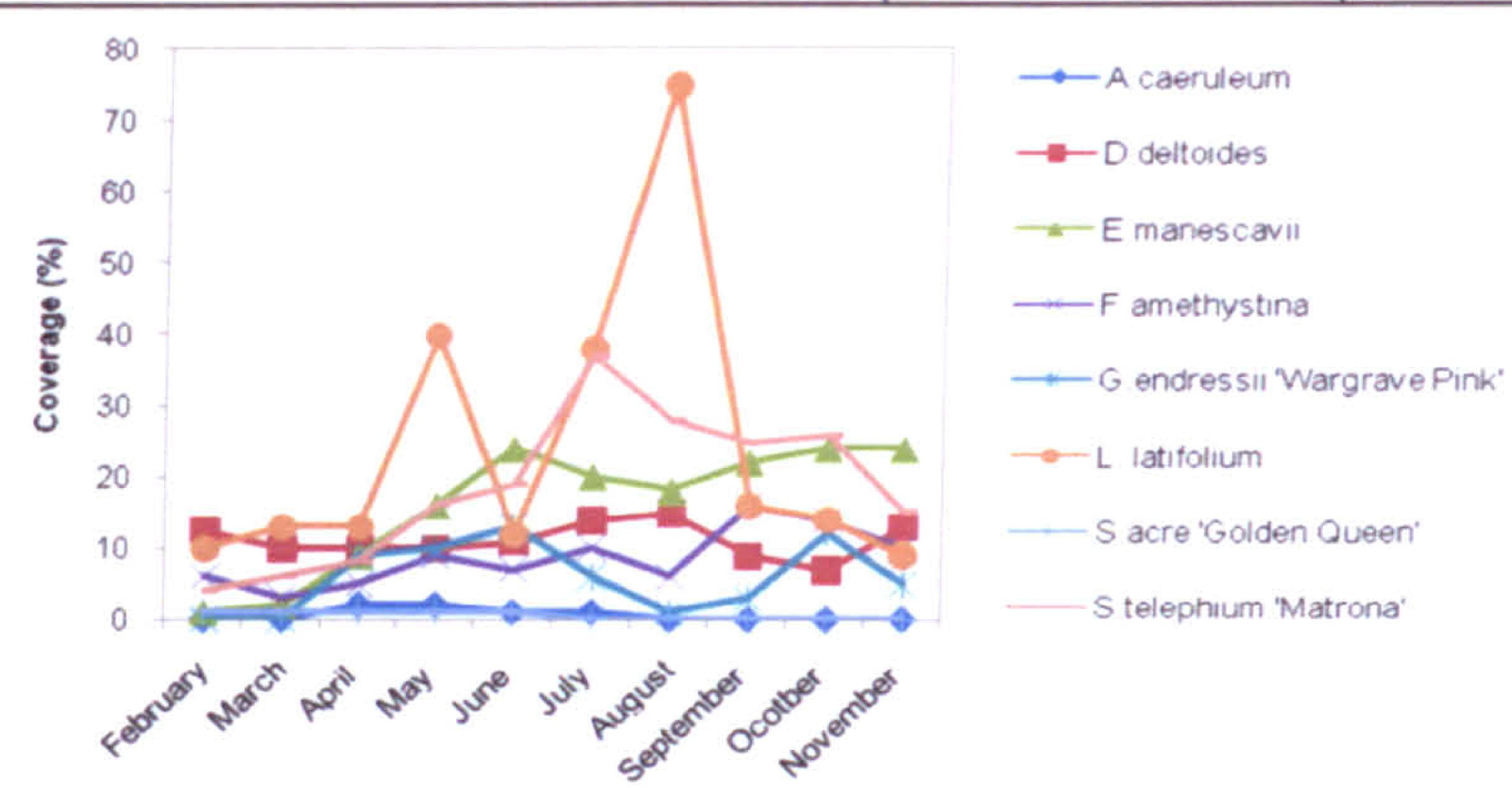


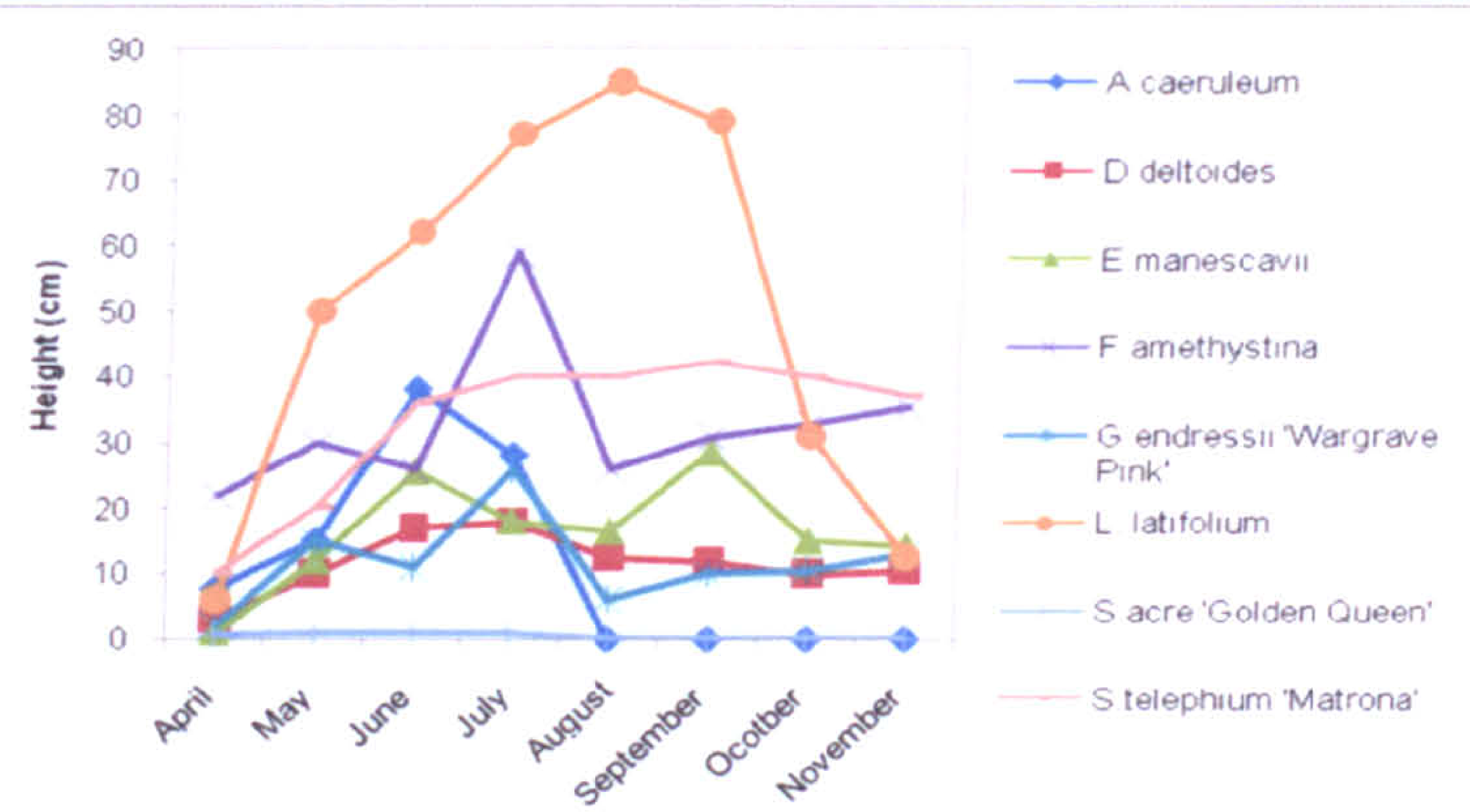


	Growth pattern
A. juniperifolia	1
D. deltoides	2
M. armeniacum	2
P. saxifraga	6
S. kamtschaticum var. floriferum 'Weihenstephaner Gold'	1
S. reflexum	1
S. uniflora	5

Quadrat 14(High diversity, Low density, Red, NW)

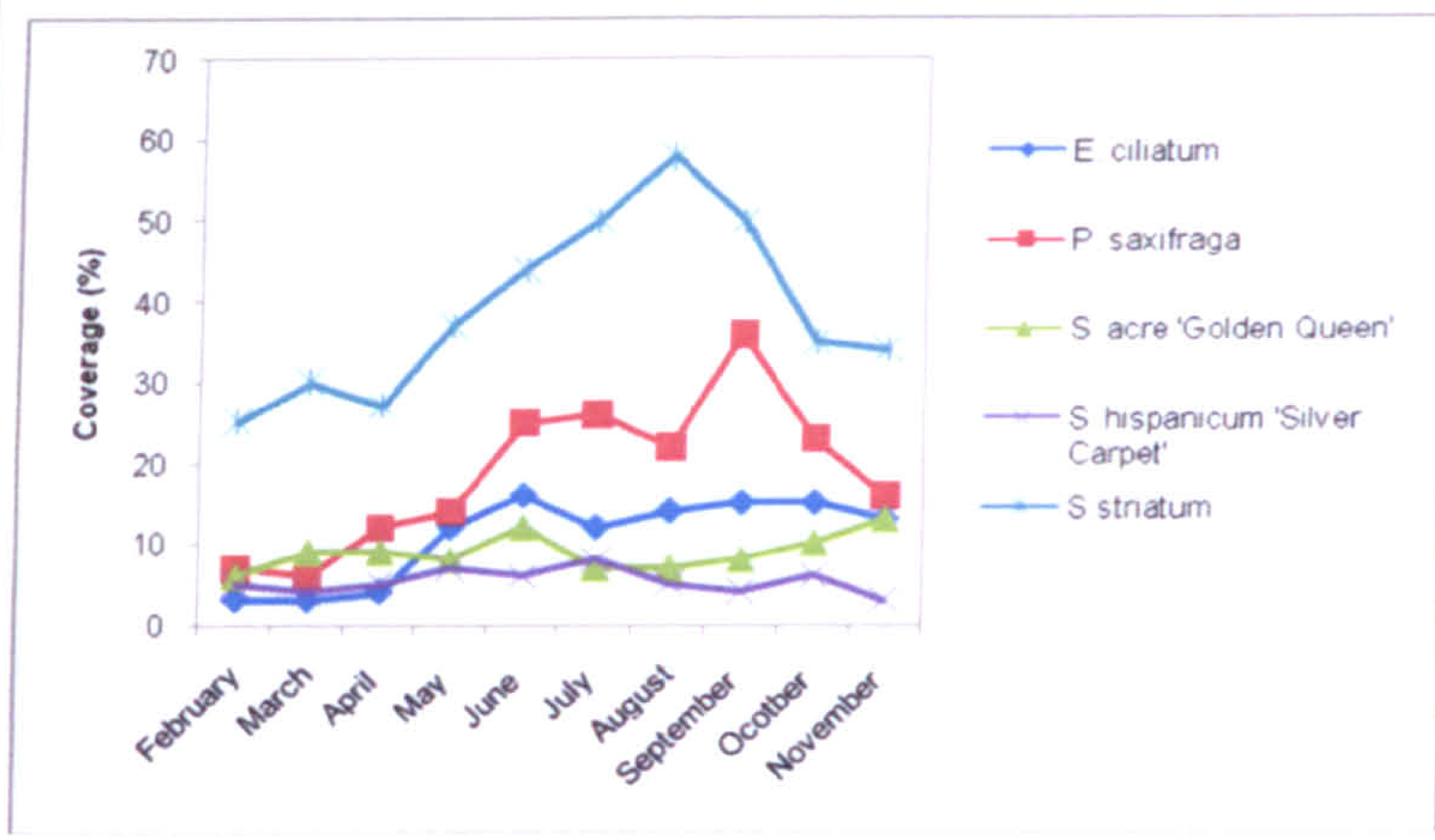
Flower succession	February	March	April	May	June	July	August	September	October	November
A. caeruleum										
D. deltoides										
E. manescavii										
F. amethystina										
G. endressii 'Wargrave Pink'										
L. latifolium										
S. acre 'Golden Queen'			No flower							
S .telephium 'Matrona'										

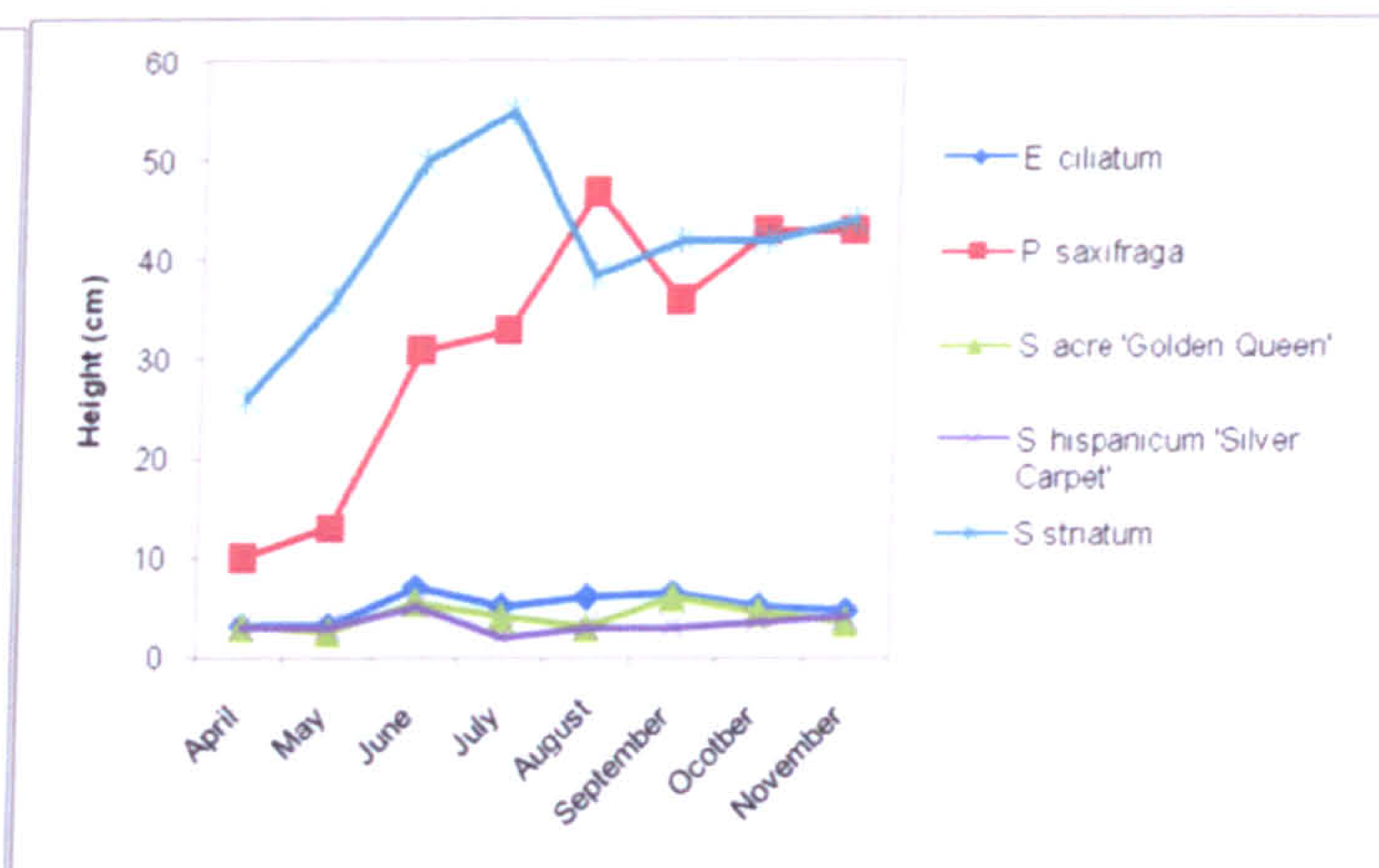




	Growth pattern
A. caeruleum	3
D. deltoides	2
E. manescavii	3
F. amethystina	2
G. endressii 'Wargrave Pink'	3
L. latifolium	3
S. acre 'Golden Queen'	1
S. telephium 'Matrona'	4

Quadrat 15 (High diversity, High density, White, NW)



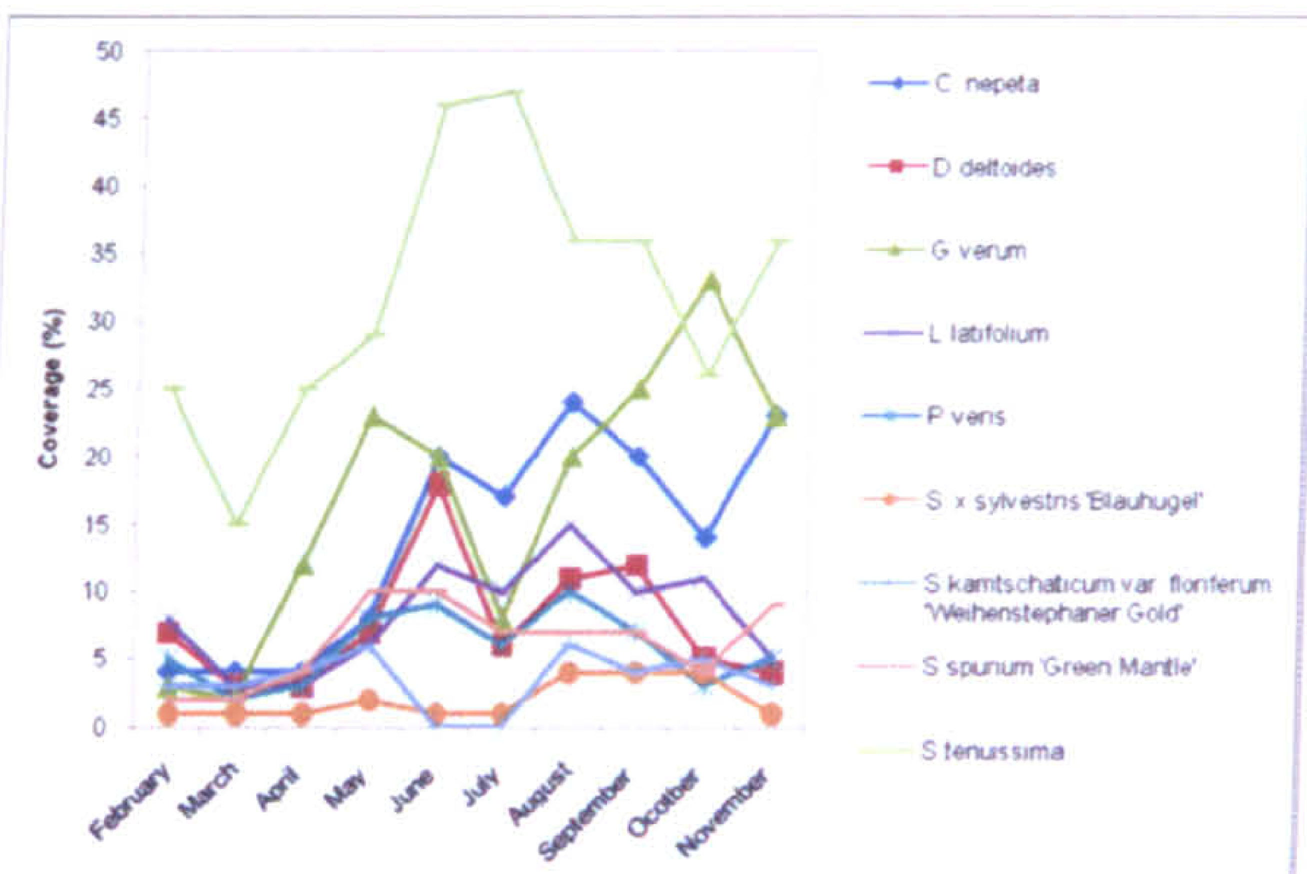


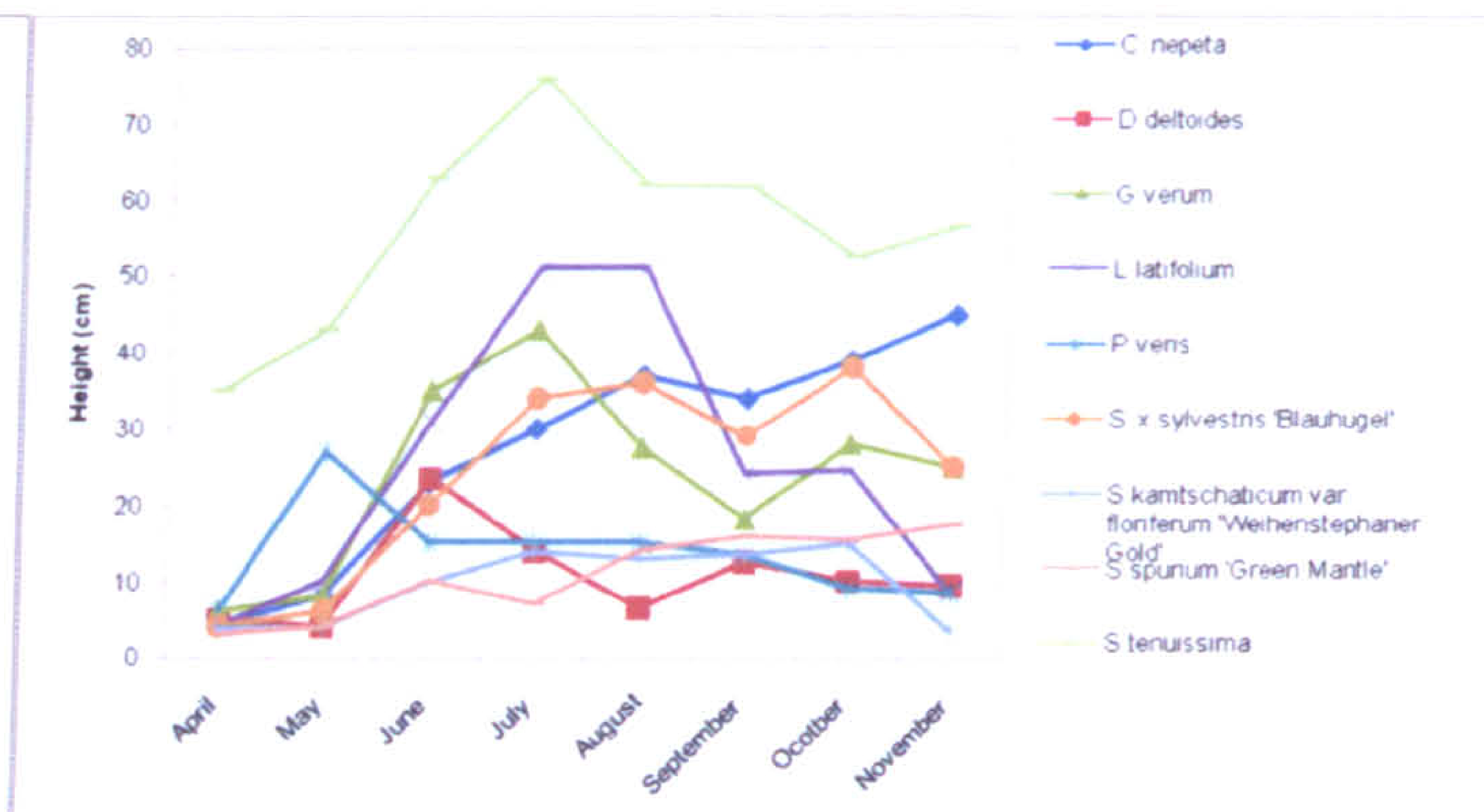
	Growth pattern
E. ciliatum	1
P. saxifraga	6
S. acre 'Golden Queen'	1
S. hispanicum 'Silver Carpet'	1
S. striatum	3

Quadrat 16 (High diversity, High density, Red, NW)

February	March	April	May	June	July	August	September	October	November
									

Flower succession										
C. nepeta										
D. deltoides										
G. verum										
L .latifolium										
P. veris										
S. x sylvestris 'Blauhügel'										
S. kamtschaticum floriferum 'Weihenstephaner Gold'	No flower									
S. spurium 'Green Mantle'	No flower									
S. tenuissima										



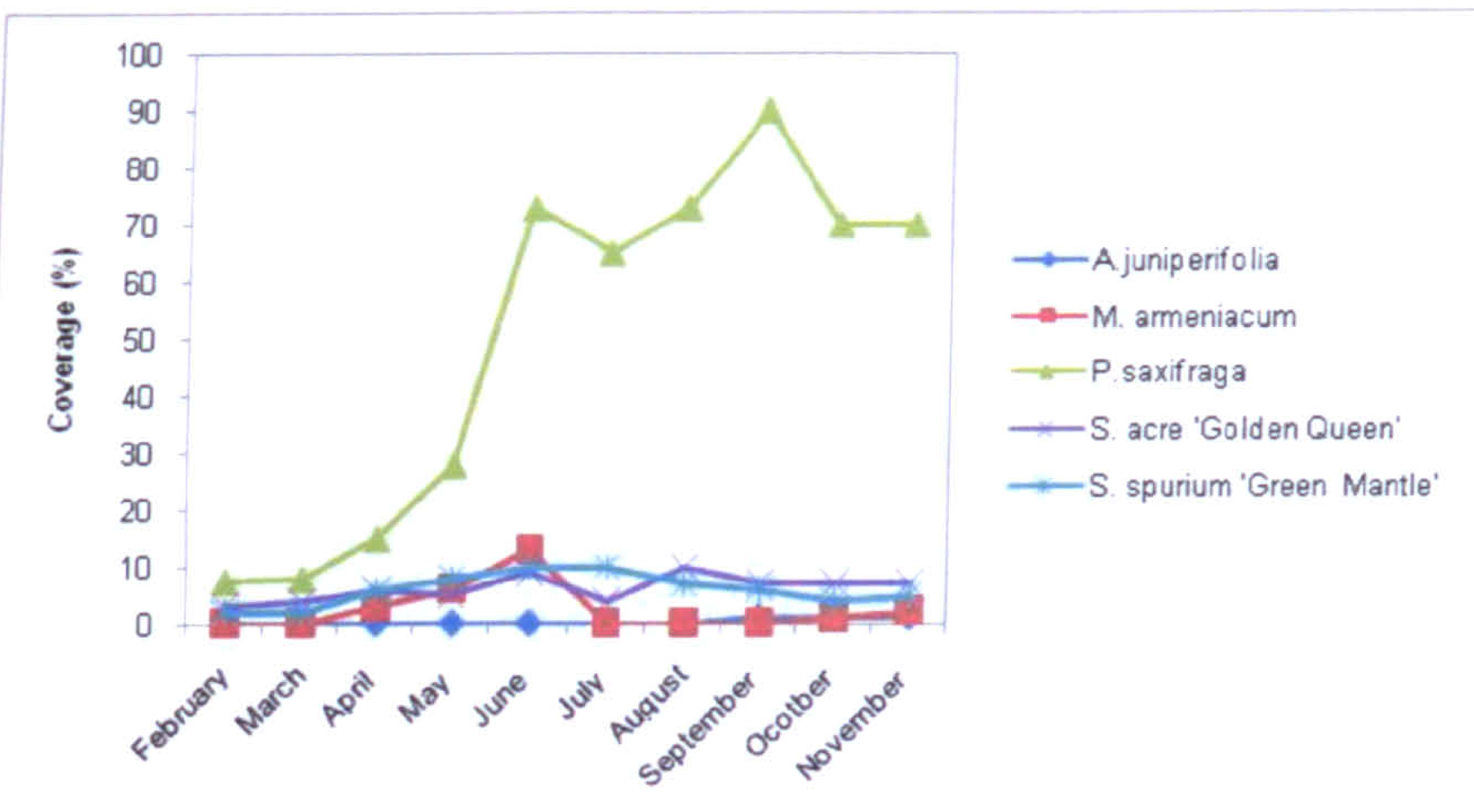


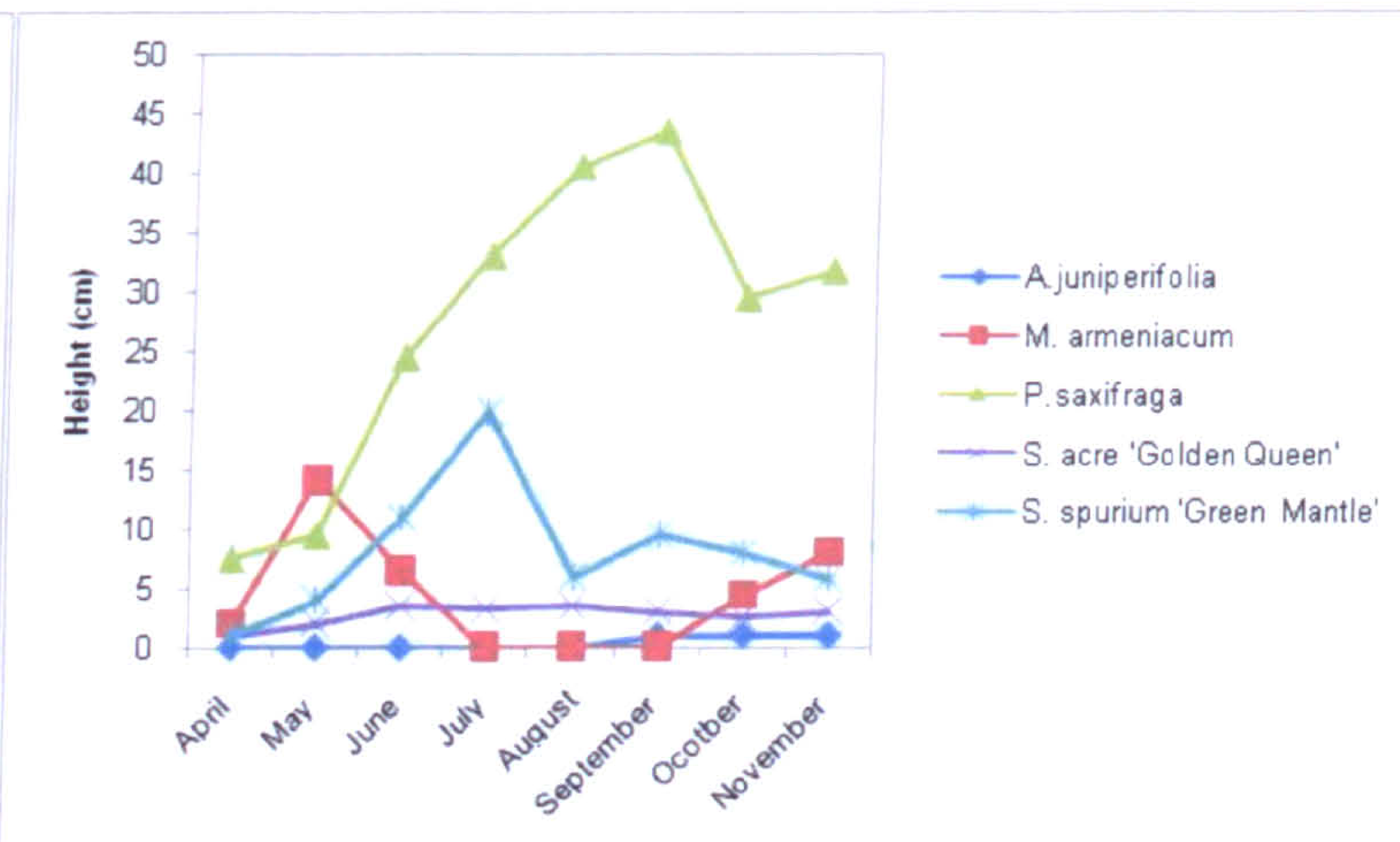
	Growth pattern
C. nepeta	6
D. deltoides	2
G. verum	3
L. latifolium	3
P. veris	1
S. x sylvestris 'Blauhügel'	4
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'	1
S. spurium 'Green Mantle'	1
S. tenuissima	6

Quadrat 17 (Low diversity, Low density, White, SW)

February	March	April	May	June	July	August	September	October	November
									

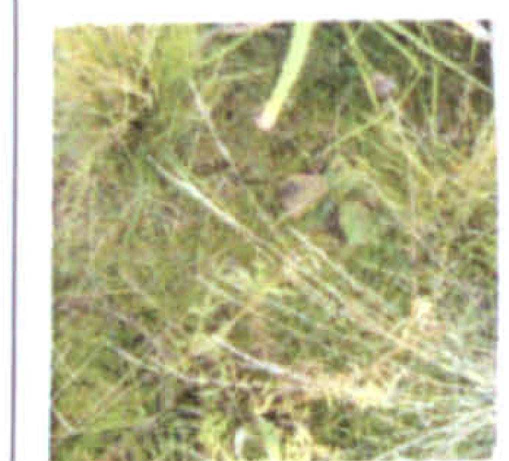
Flower succession								
A. juniperifolia	No flower							
M. armeniacum								
P. saxifraga								
S. acre 'Golden Queen'								
S. spurium 'Green Mantle'								

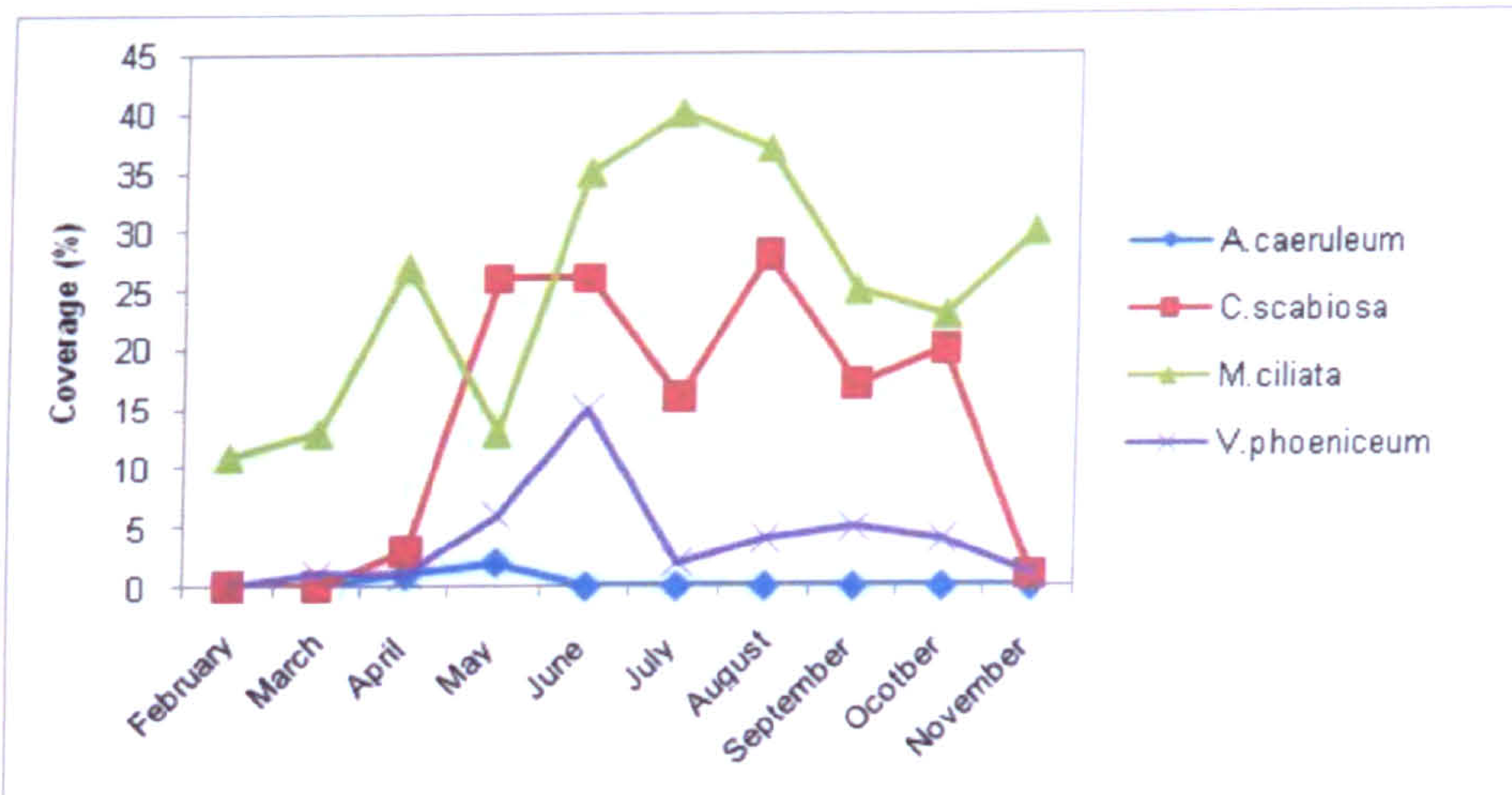


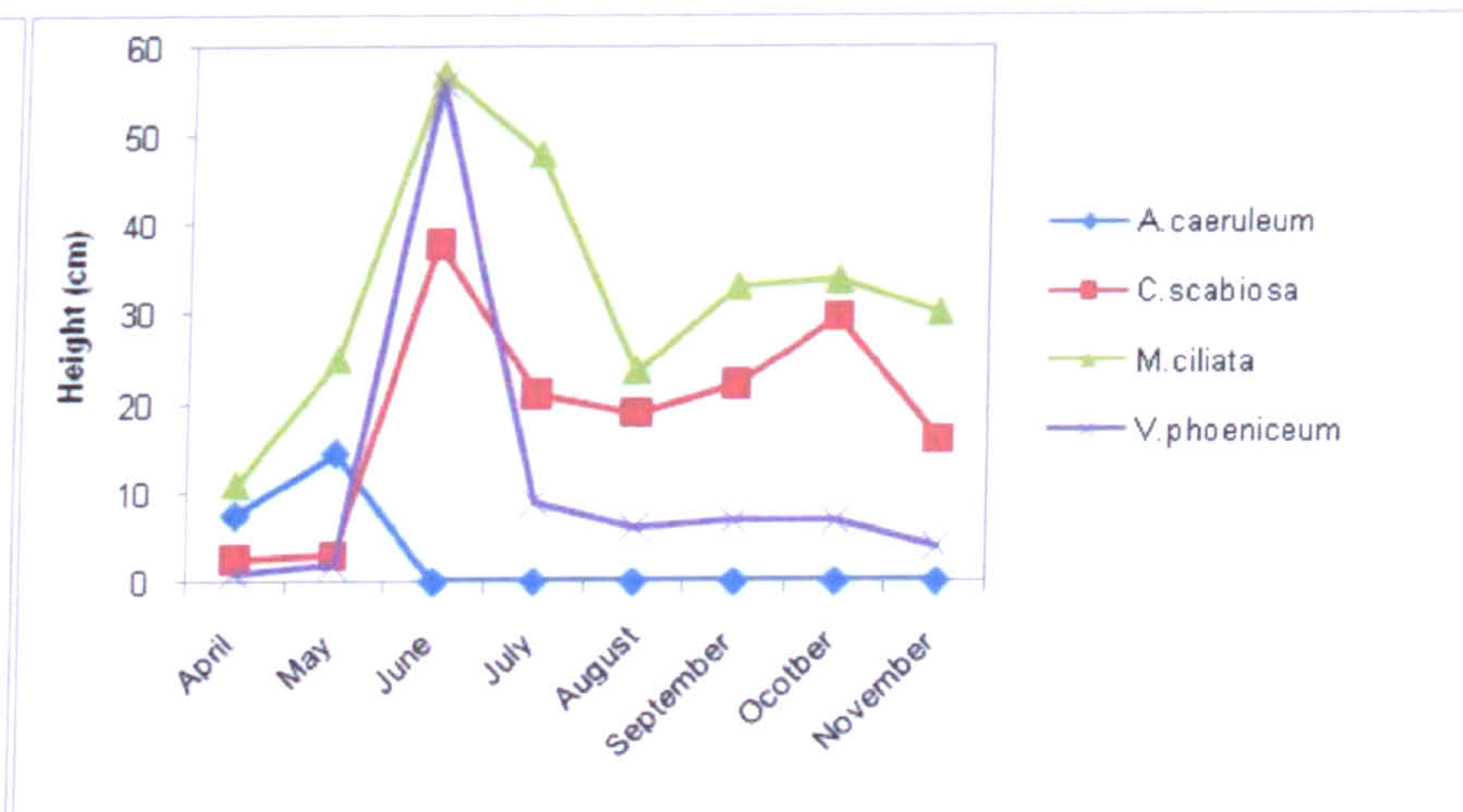


	Growth pattern
A. juniperifolia	1
M. armeniacum	2
P. saxifraga	6
S. acre 'Golden Queen'	1
S. spurium 'Green Mantle'	1

Quadrat 18 (Low diversity, Low density, Red, SW)

February	March	April	May	June	July	August	September	October	November
									
Flower succession									
A. caeruleum	No flower								
C. scabiosa									
M. ciliata									
V. phoeniceum									

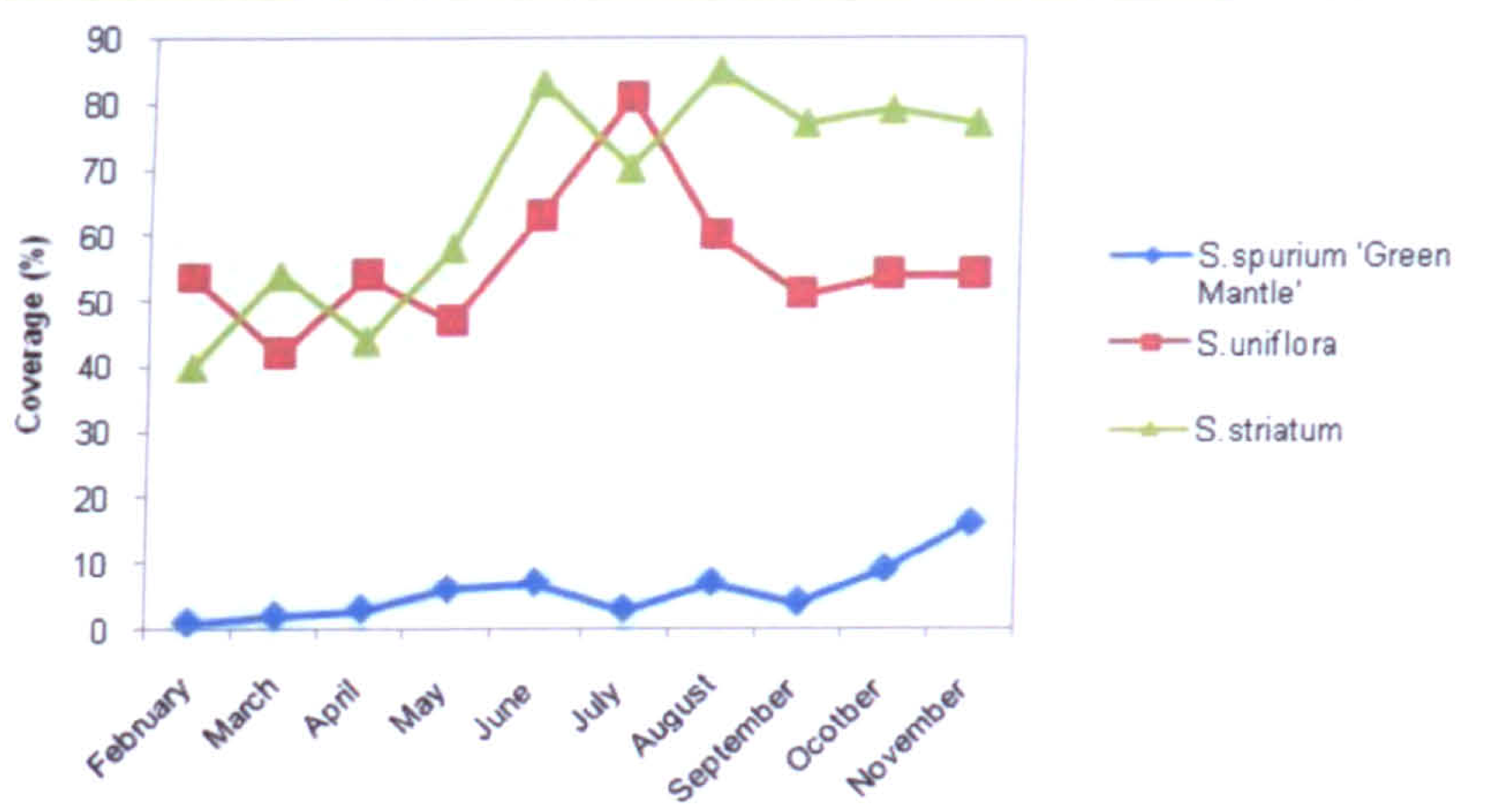


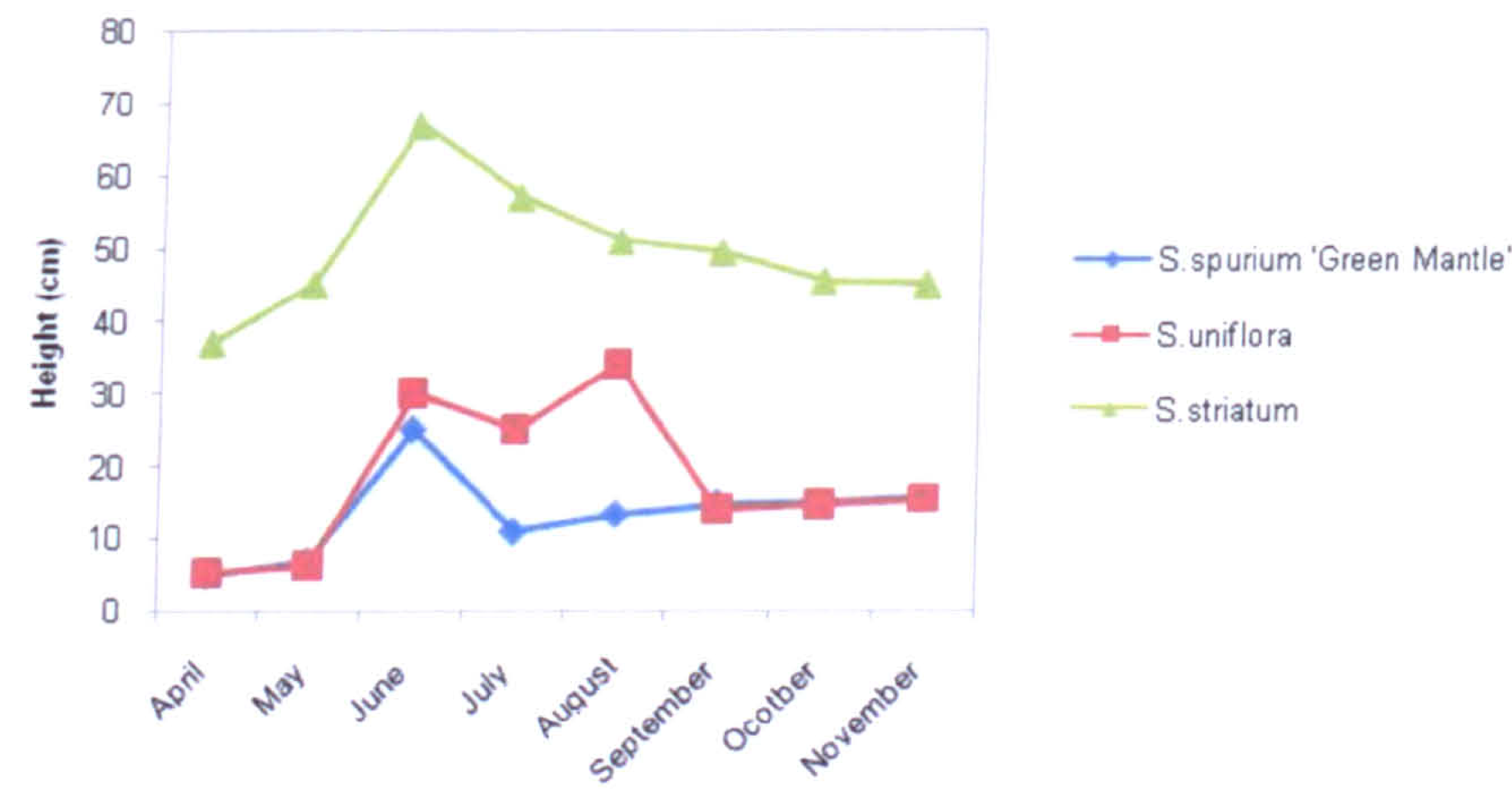


	Growth pattern
A. caeruleum	3
C. scabiosa	3
M. ciliata	5
V. phoeniceum	3

Quadrat 19 (Low diversity, High density, White, SW)

February	March	April	May	June	July	August	September	October	November
									
Flower succession									
S. spurium 'Green Mantle'		No flower							
S. uniflora									
S. striatum									



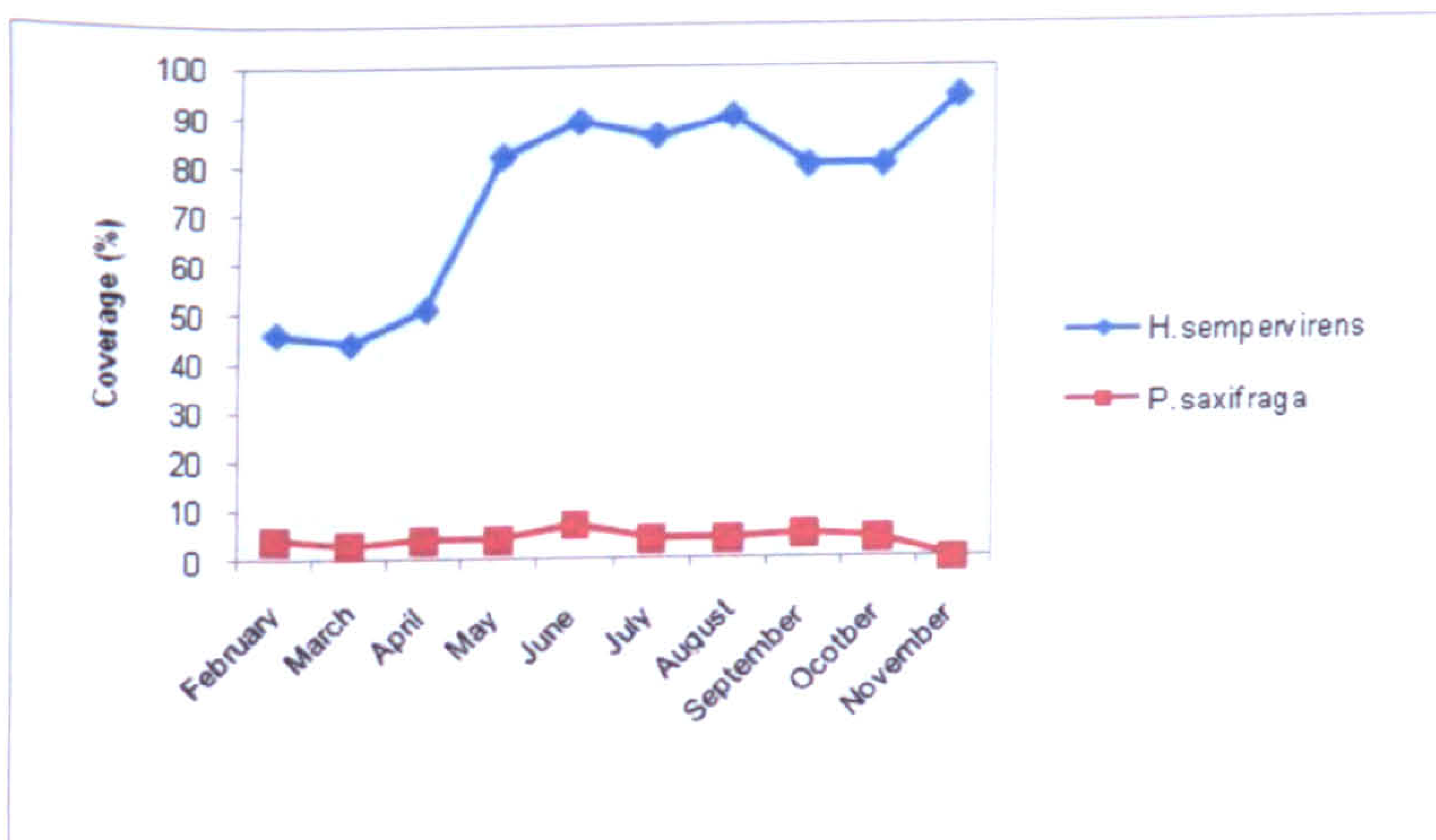


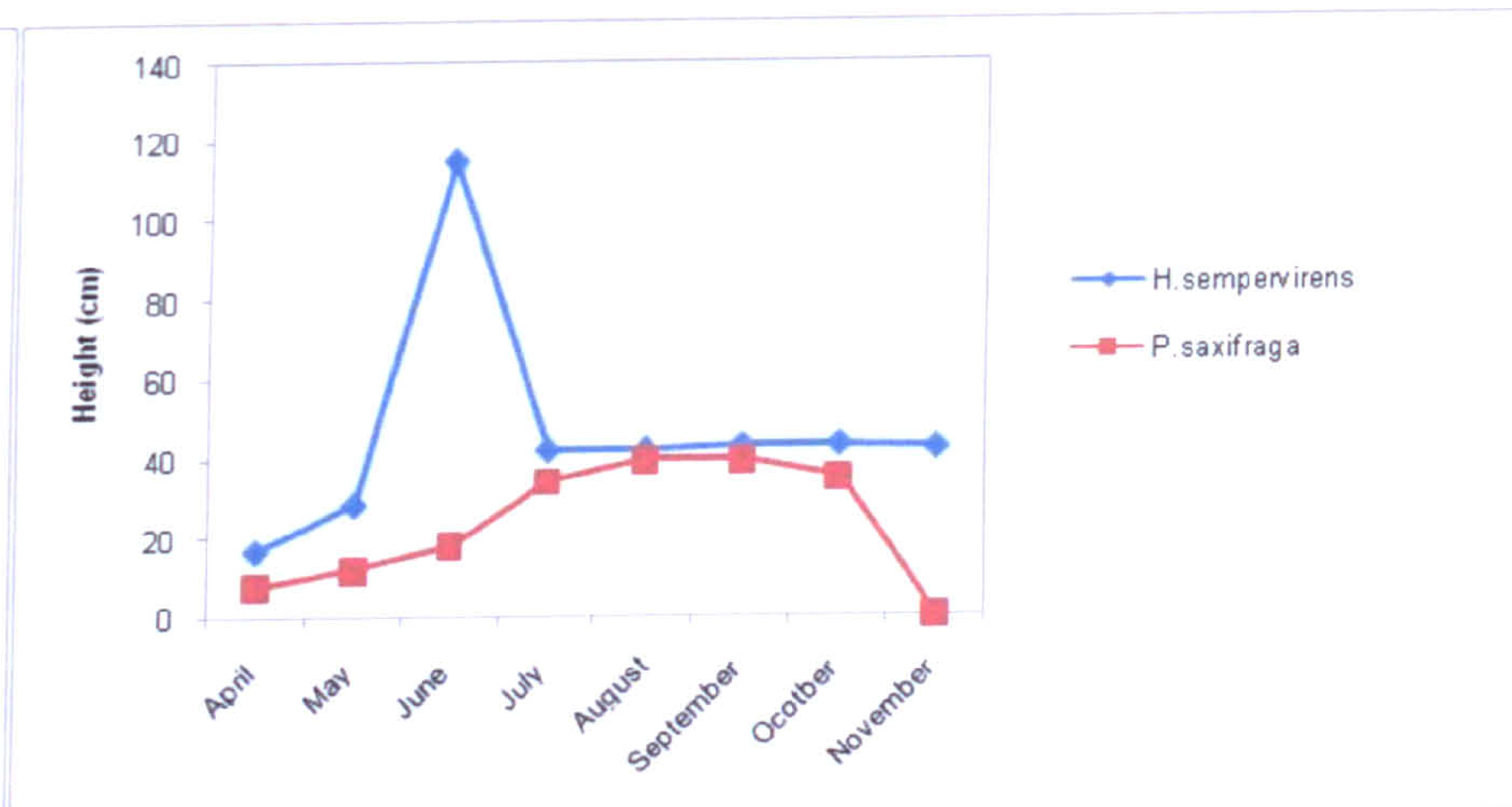
	Growth pattern
S. spurium 'Green Mantle'	1
S. uniflora	5
S. striatum	3

Quadrat 20 (Low diversity, High density, Red, SW)

February	March	April	May	June	July	August	September	October	November

Flower succession										
H. sempervirens					(shaded)					
P. saxifraga										



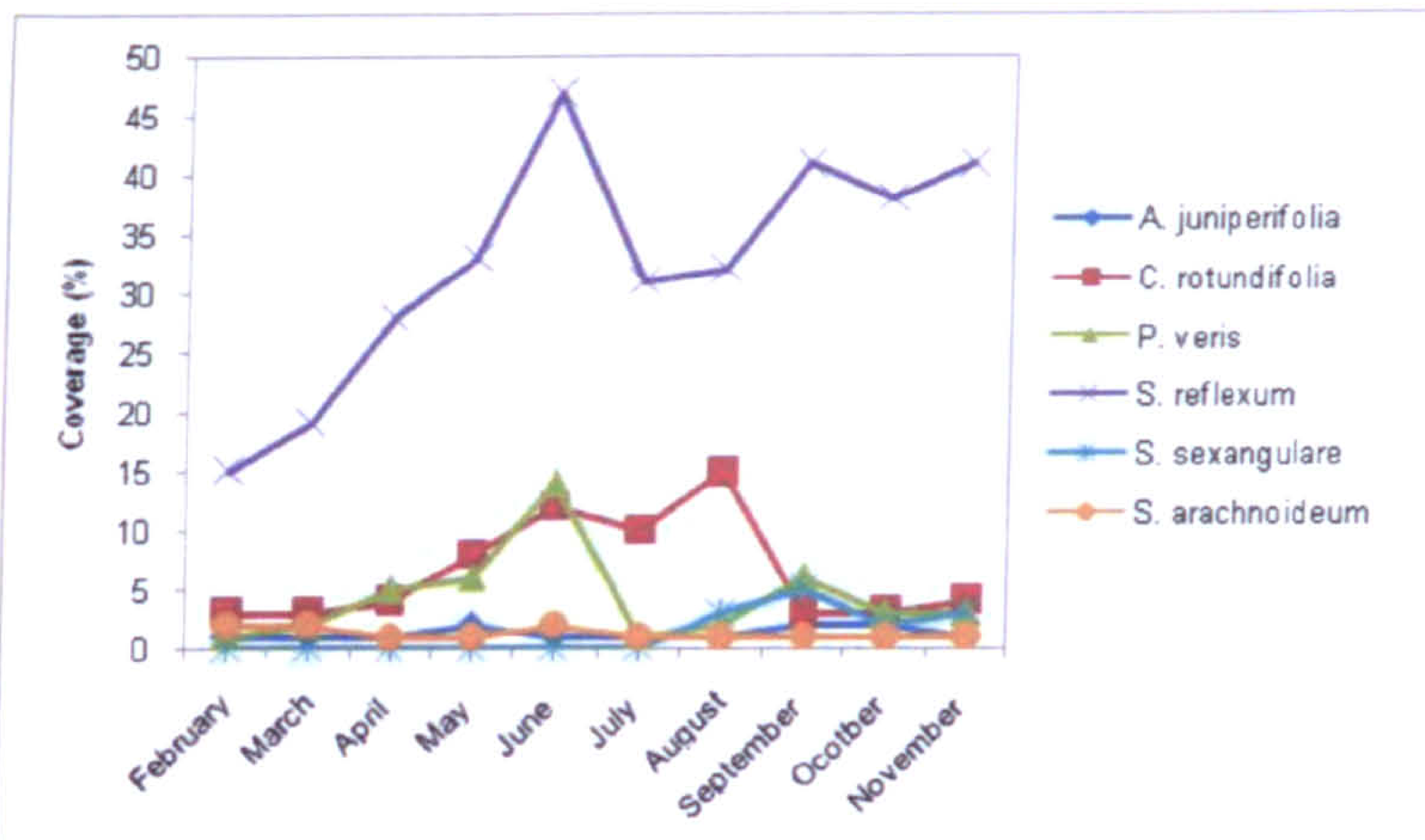


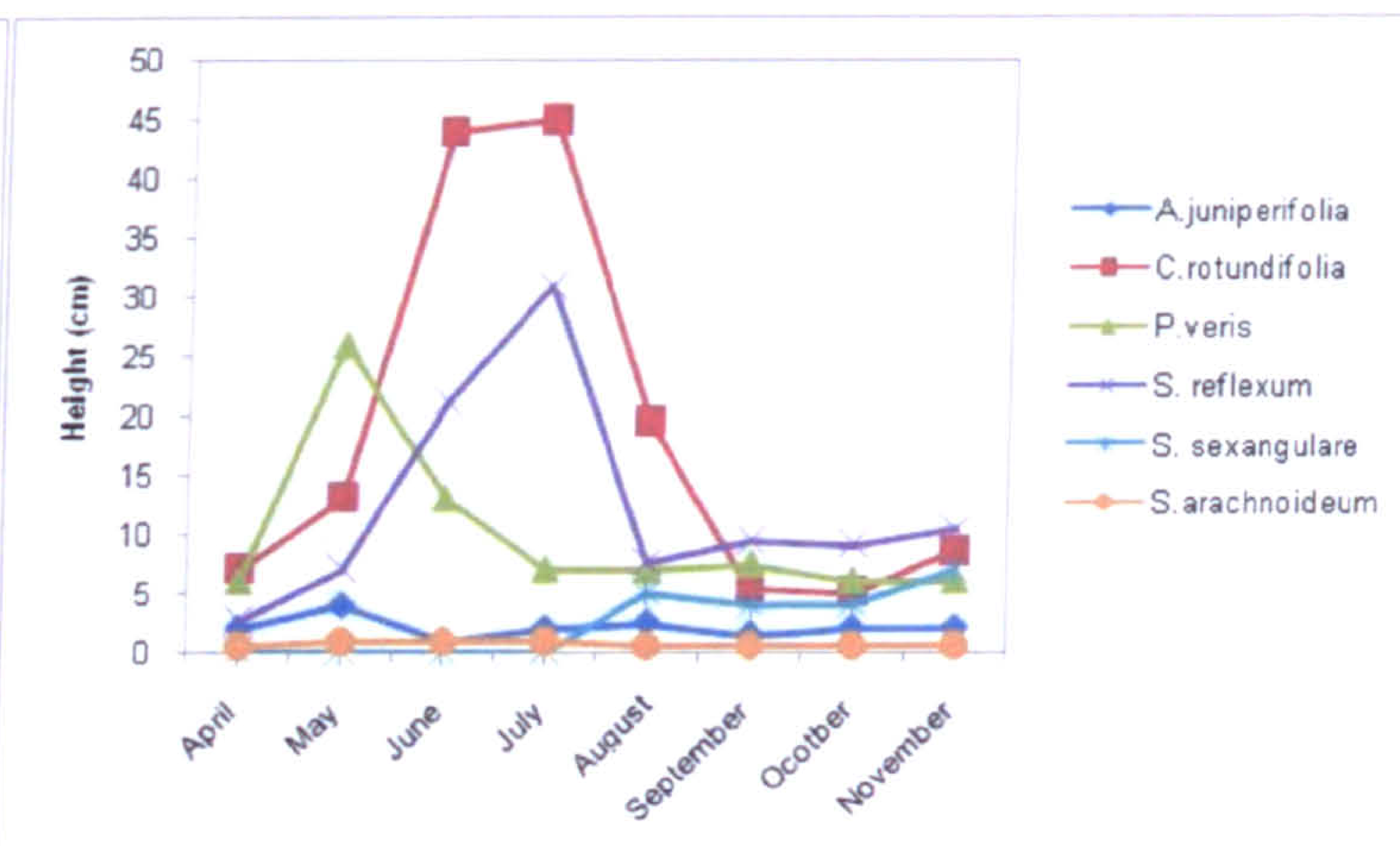
	Growth pattern
H .sempervirens	5
P. saxifraga	6

Quadrat 21 (High diversity, Low density, White, SW)

February	March	April	May	June	July	August	September	October	November

Flower succession										
A. juniperifolia										
C. rotundifolia										
P. veris										
S. reflexum										
S. sexangulare	No flower									
S. arachnoideum	No flower									



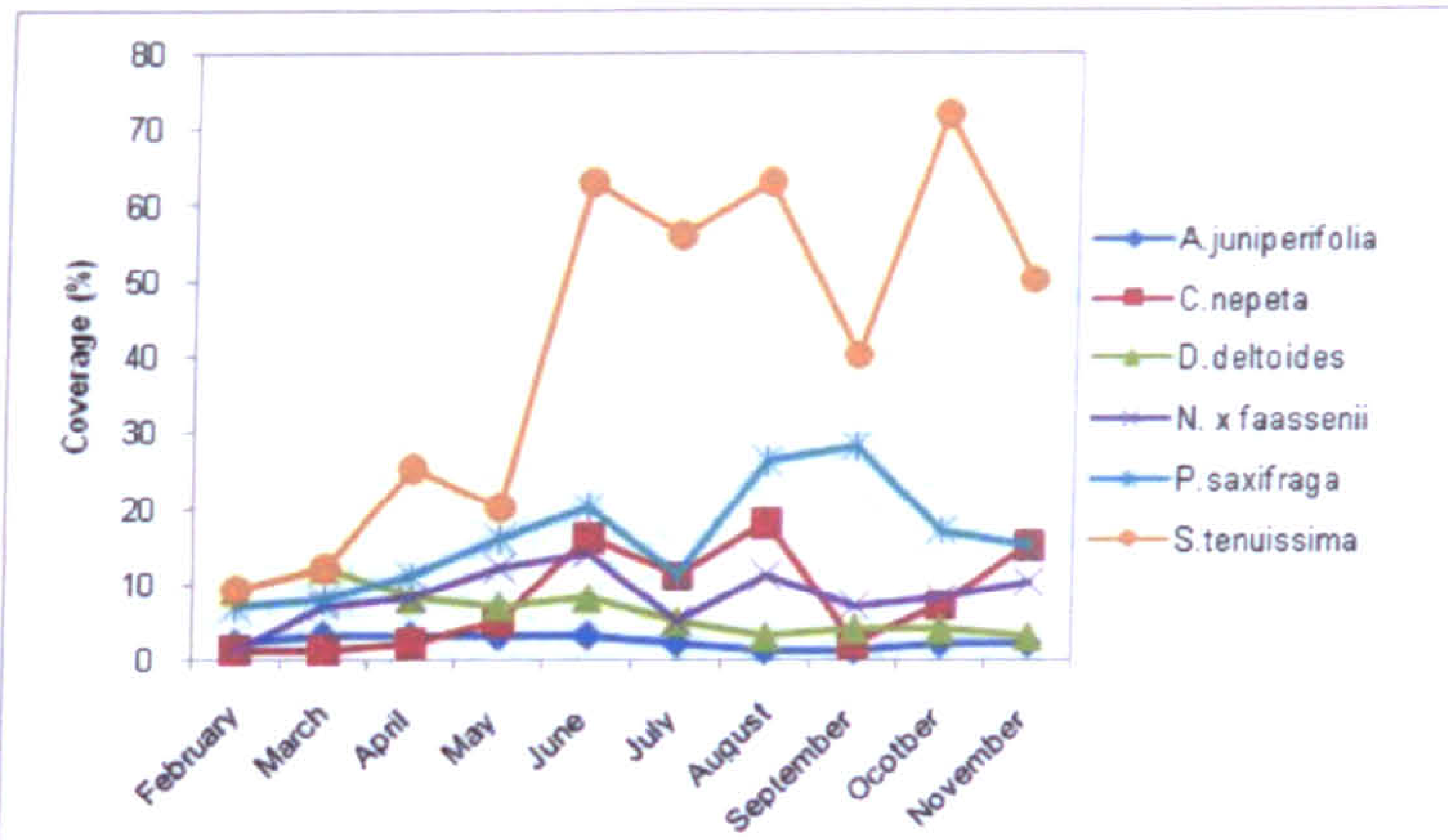


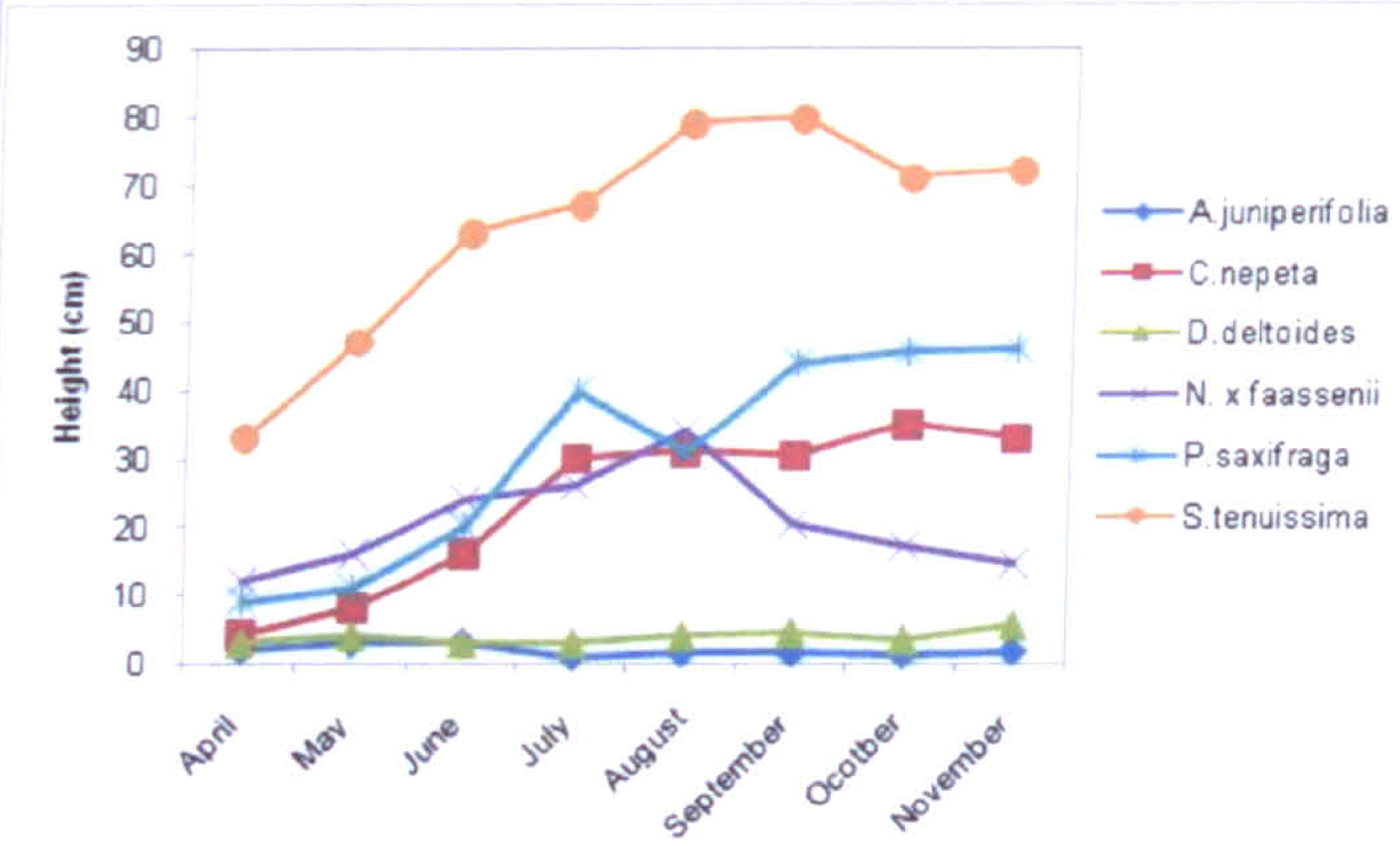
	Growth pattern
A. juniperifolia	1
C. rotundifolia	2
P. veris	1
S. reflexum	1
S. sexangulare	1
S. arachnoideum	1

Quadrat 22 (High diversity, Low density, Red, SW)

February	March	April	May	June	July	August	September	October	November

Flower succession	April	May	June	July	August	September	October	November
A. juniperifolia		■						
C. nepeta				■	■			
D. deltoides								
N. x faassenii				■				
P. saxifraga					■	■	■	
S. tenuissima			■					



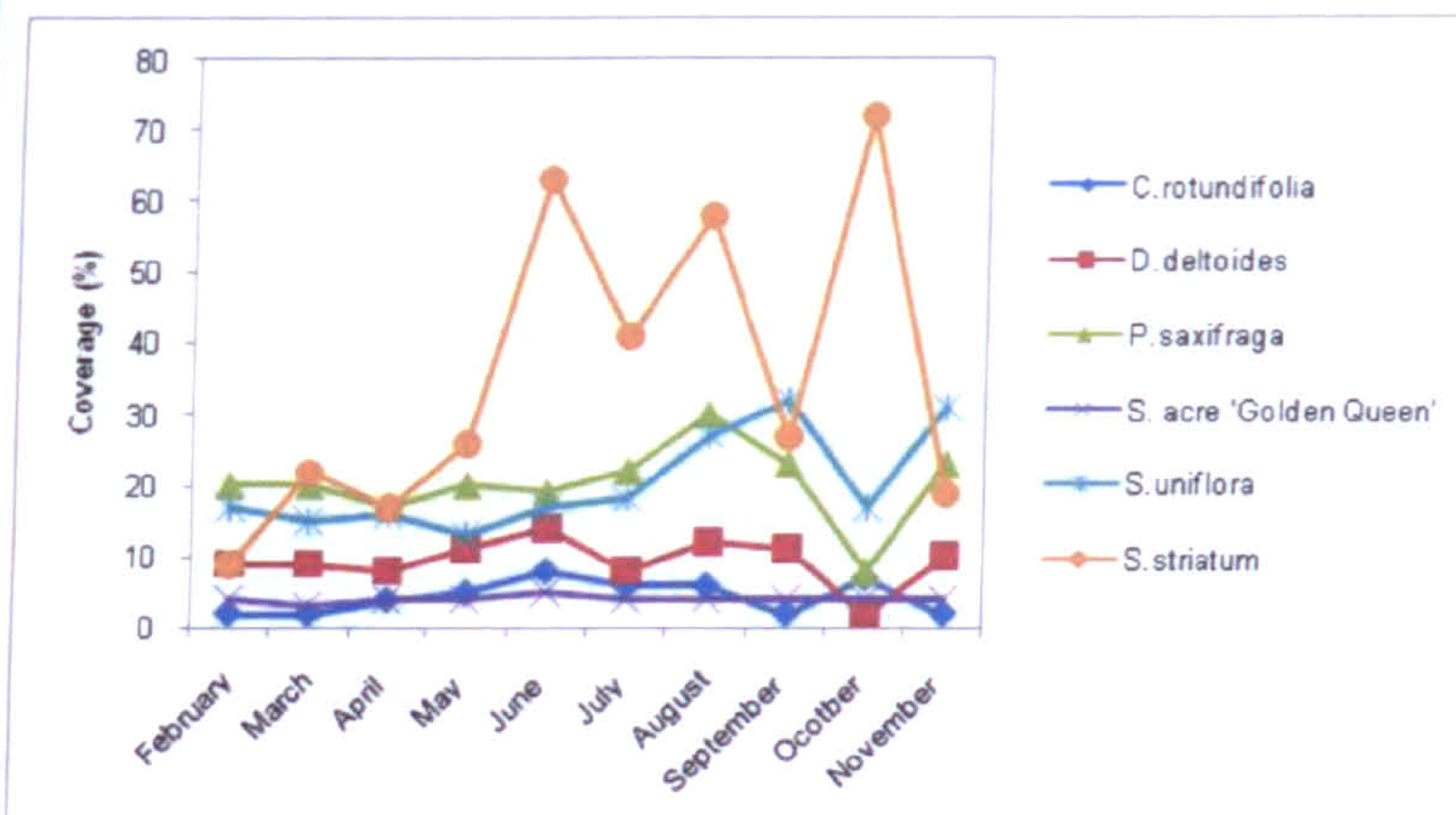


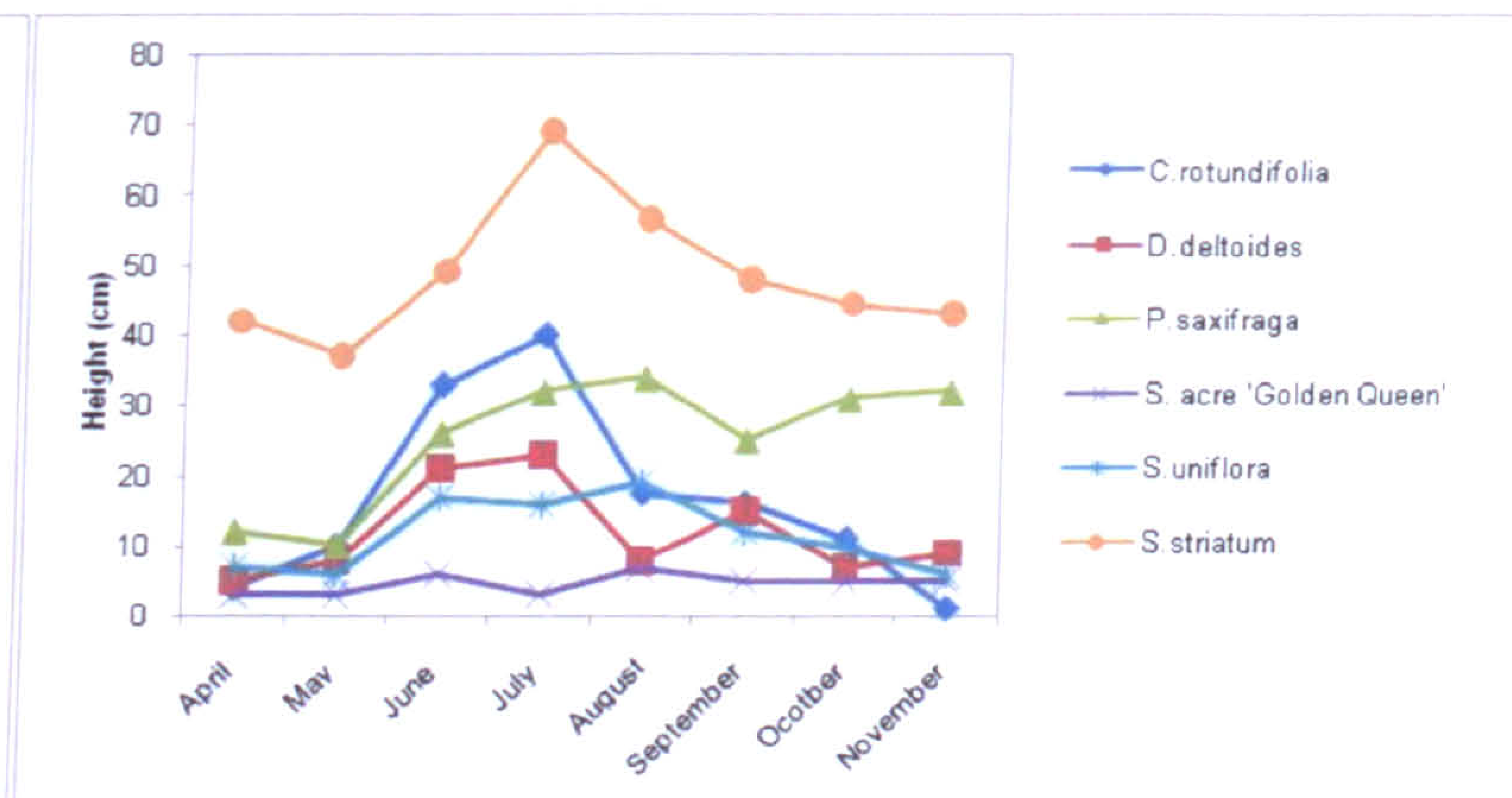
	Growth pattern
A. juniperifolia	1
C. nepeta	6
D. deltoides	2
N. x faassenii	5
P. saxifraga	6
S. tenuissima	6

Quadrat 23 (High diversity, High density, White, SW)

February	March	April	May	June	July	August	September	October	November

Flower succession	February	March	April	May	June	July	August	September	October	November
C. rotundifolia										
D. deltoides										
P. saxifraga										
S. acre 'Golden Queen'										
S. uniflora										
S. striatum										



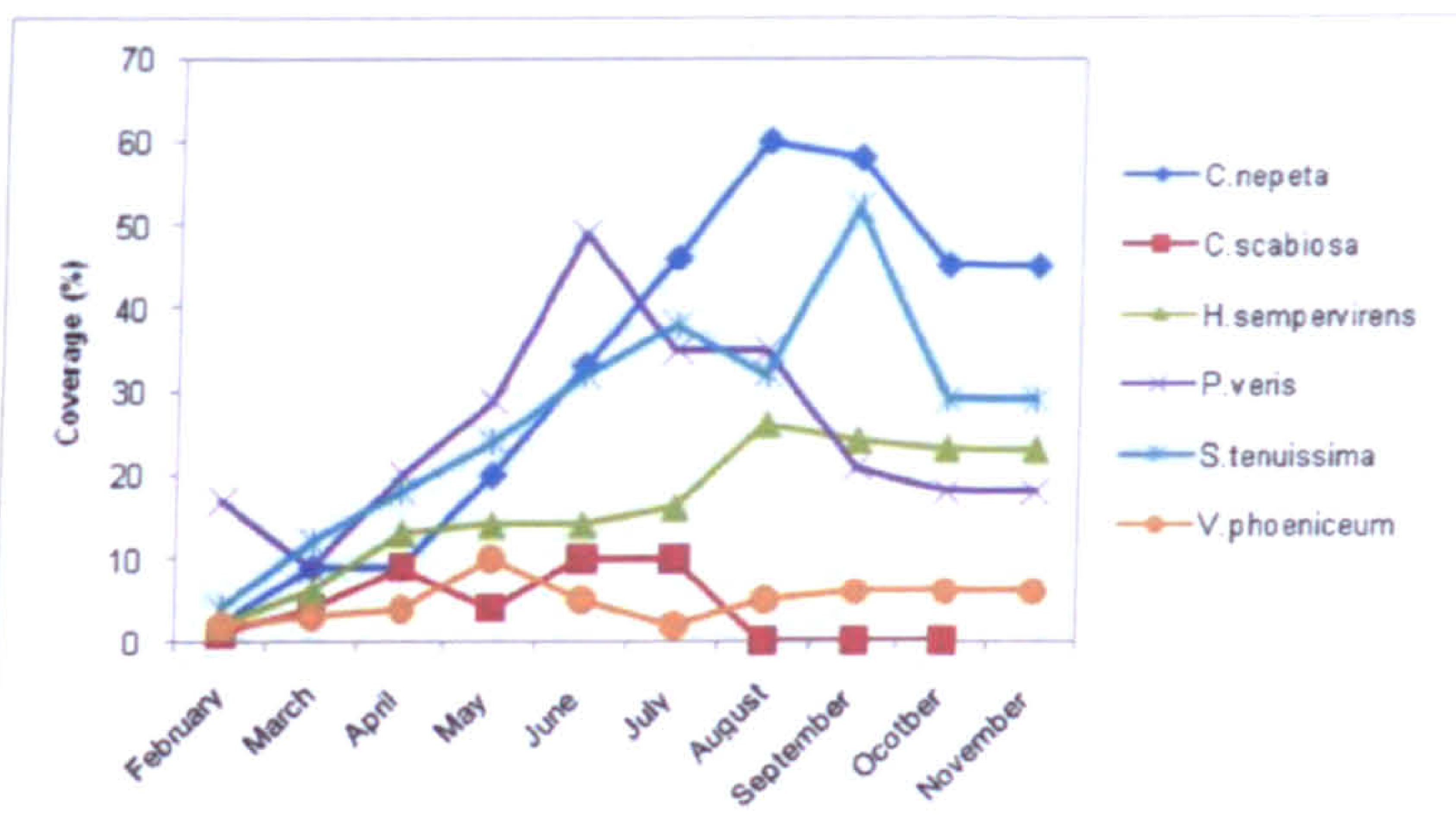


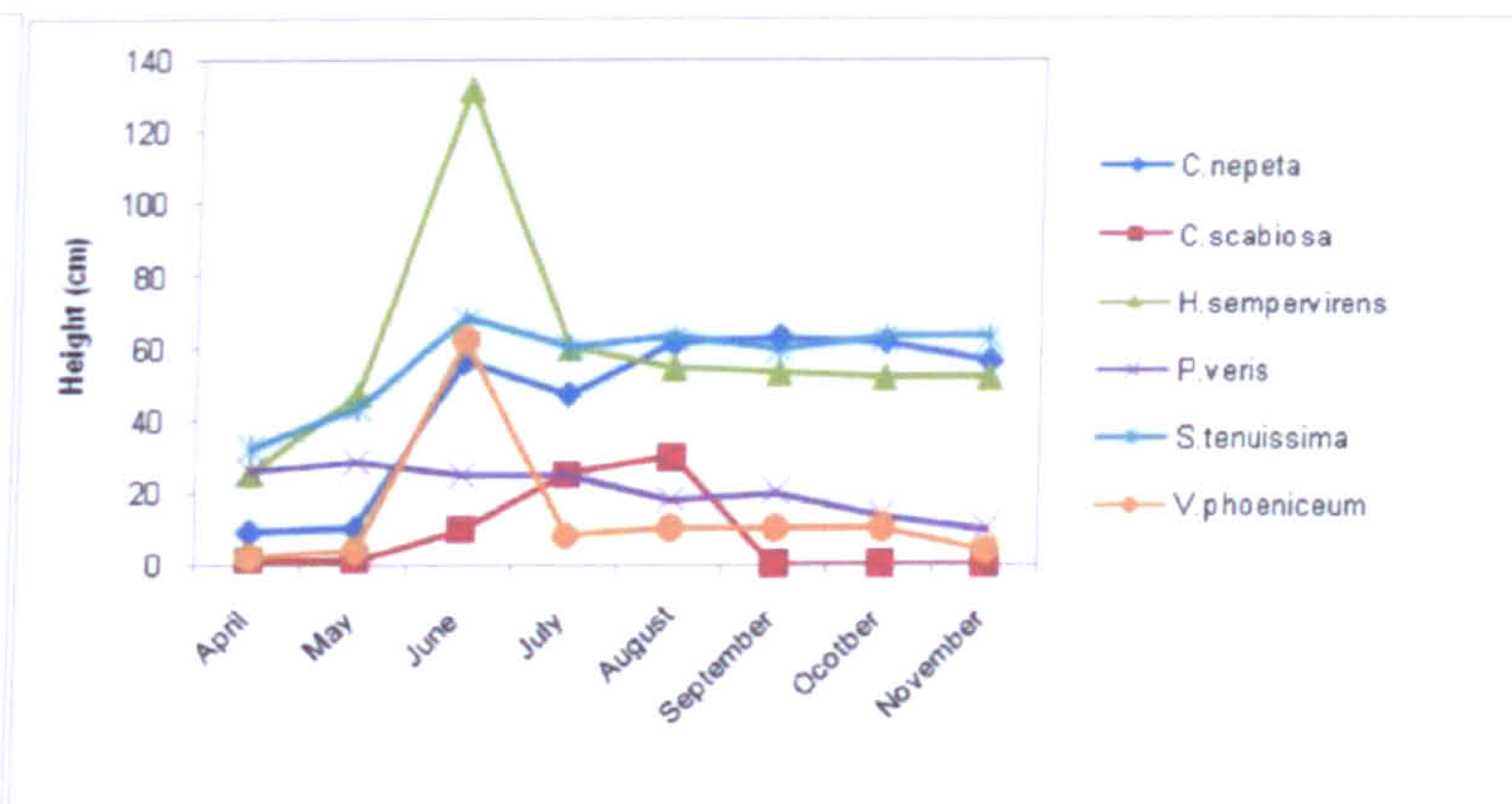
	Growth pattern
C. rotundifolia	2
D. deltoides	2
P. saxifraga	6
S. acre 'Golden Queen'	1
S. uniflora	5
S. striatum	3

Quadrat 24(High diversity, High density, Red, SW)

February	March	April	May	June	July	August	September	October	November

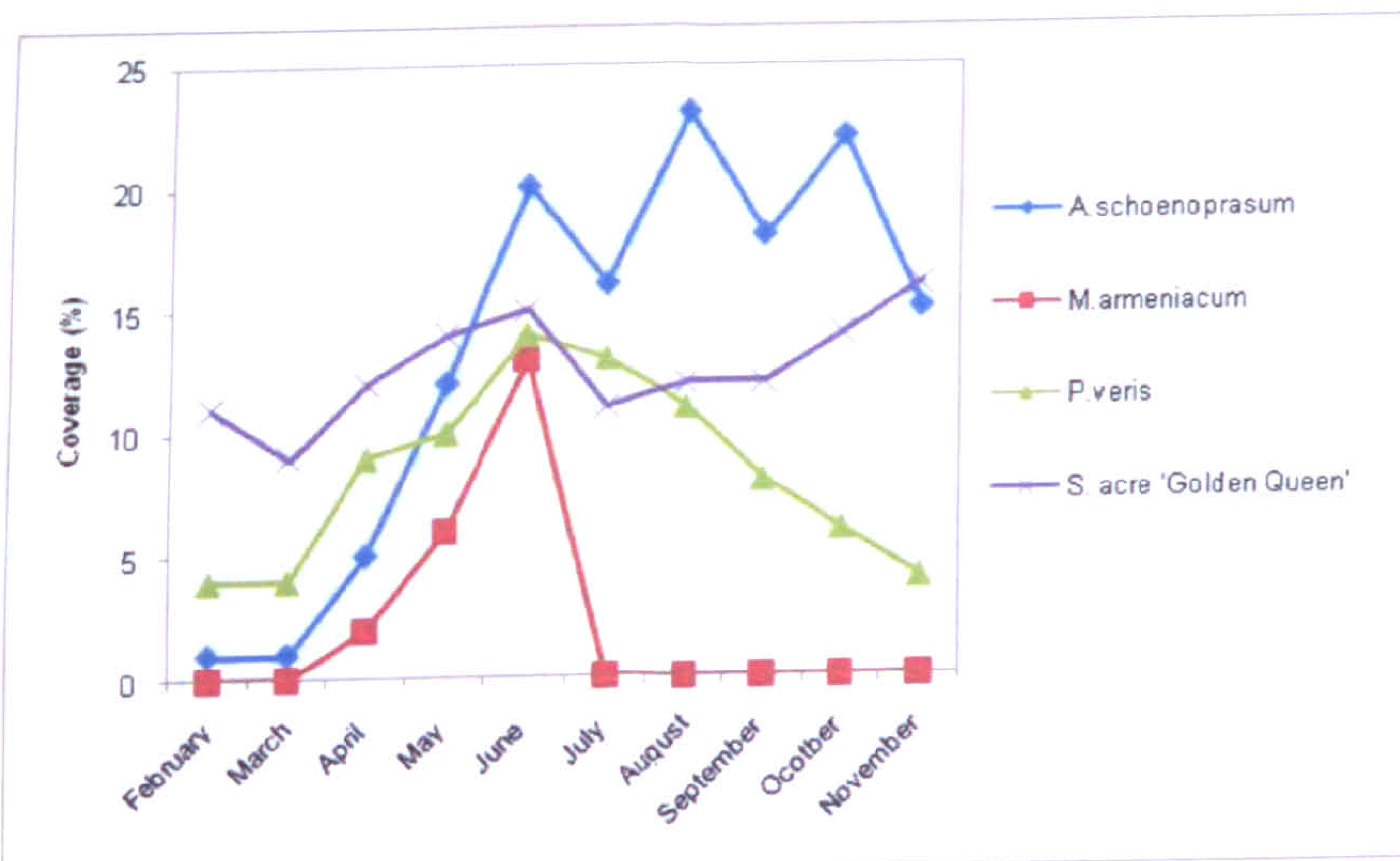
Flower succession										
C. nepeta										
C. scabiosa										
H. sempervirens										
P. veris										
S. tenuissima										
V. phoeniceum										

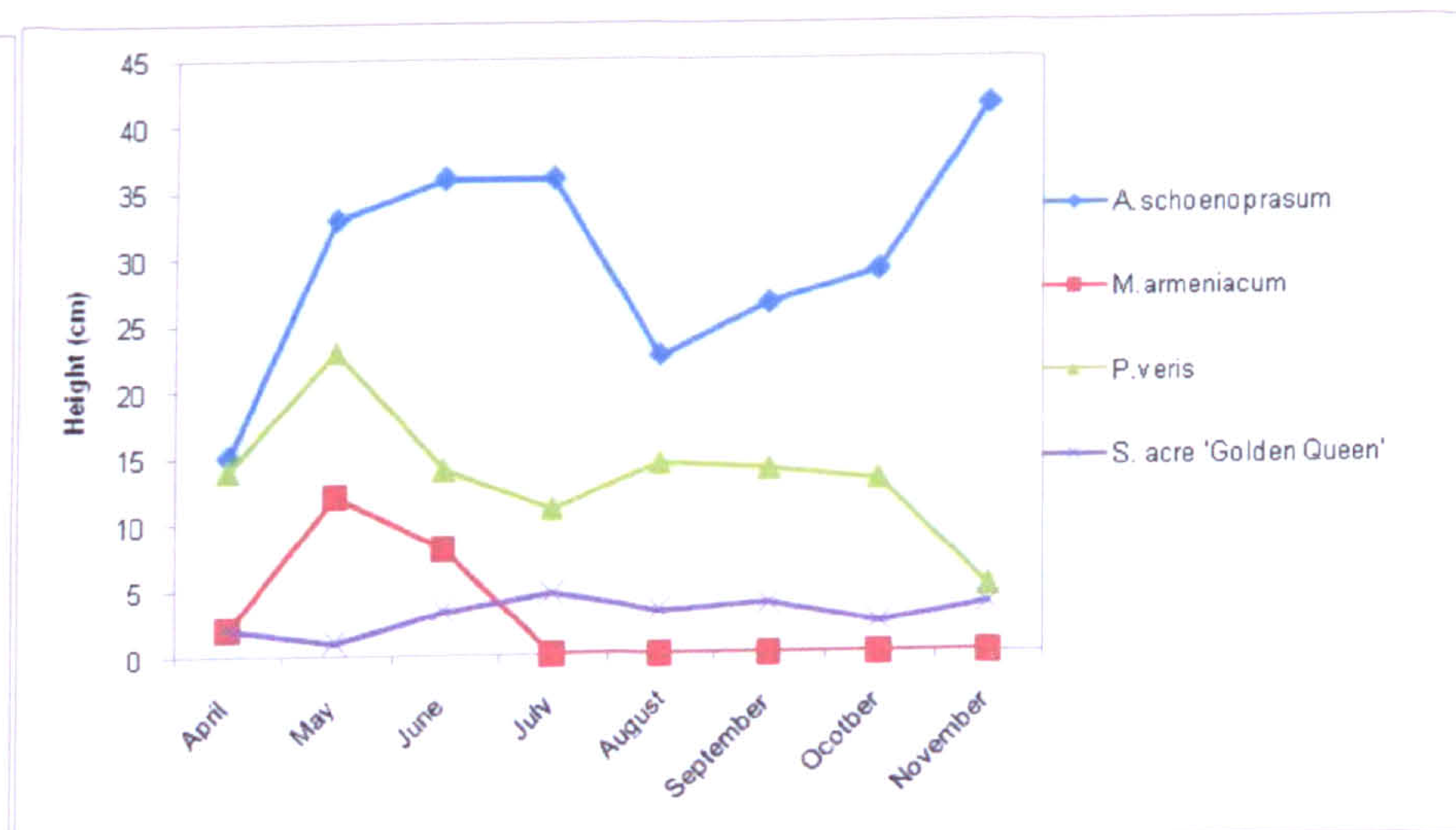




	Growth pattern
C. nepeta	6
C. scabiosa	3
H. sempervirens	5
P. veris	1
S. tenuissima	6
V. phoeniceum	3

Quadrat 25 (Low diversity, Low density, White, SE)

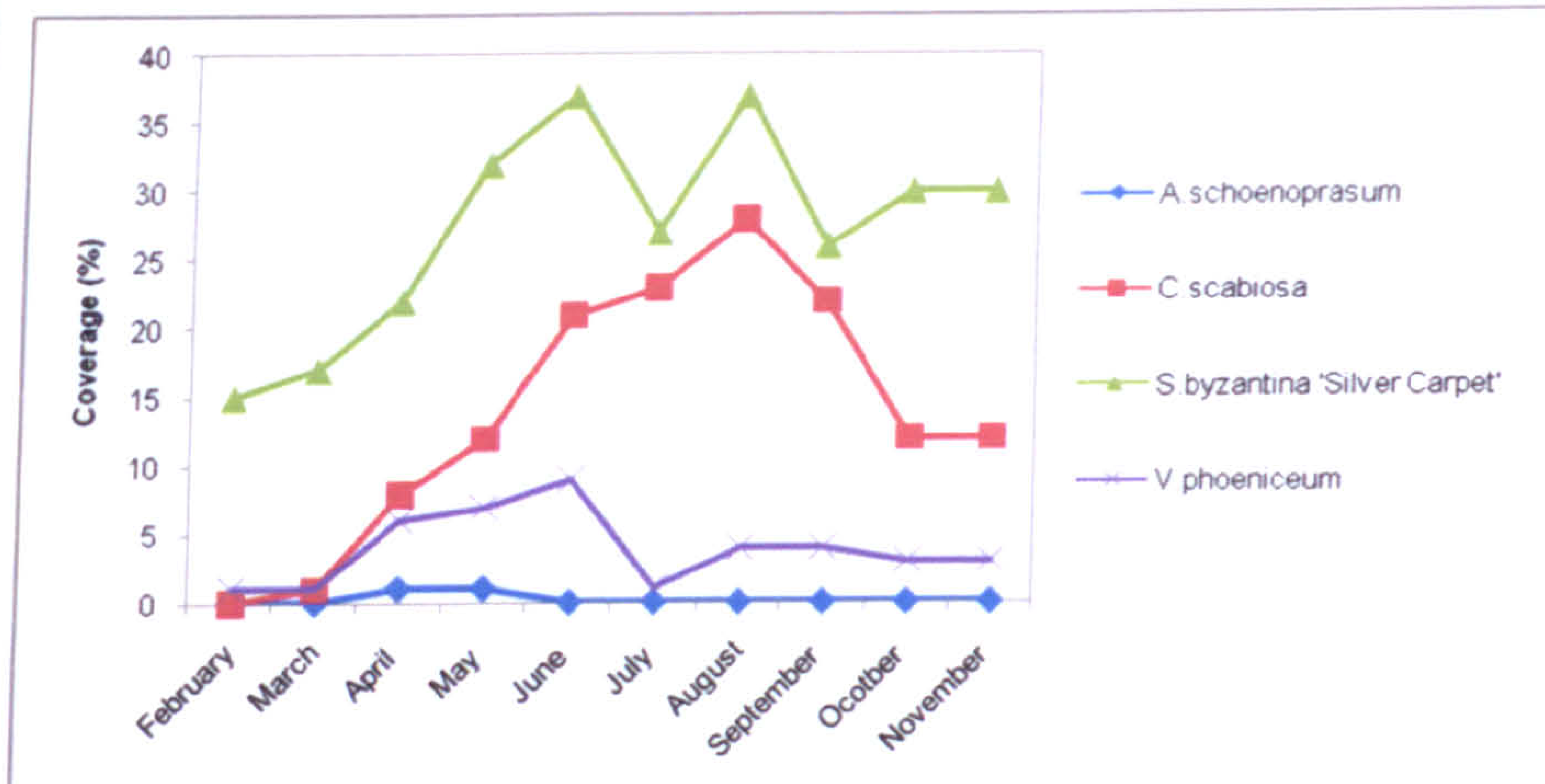


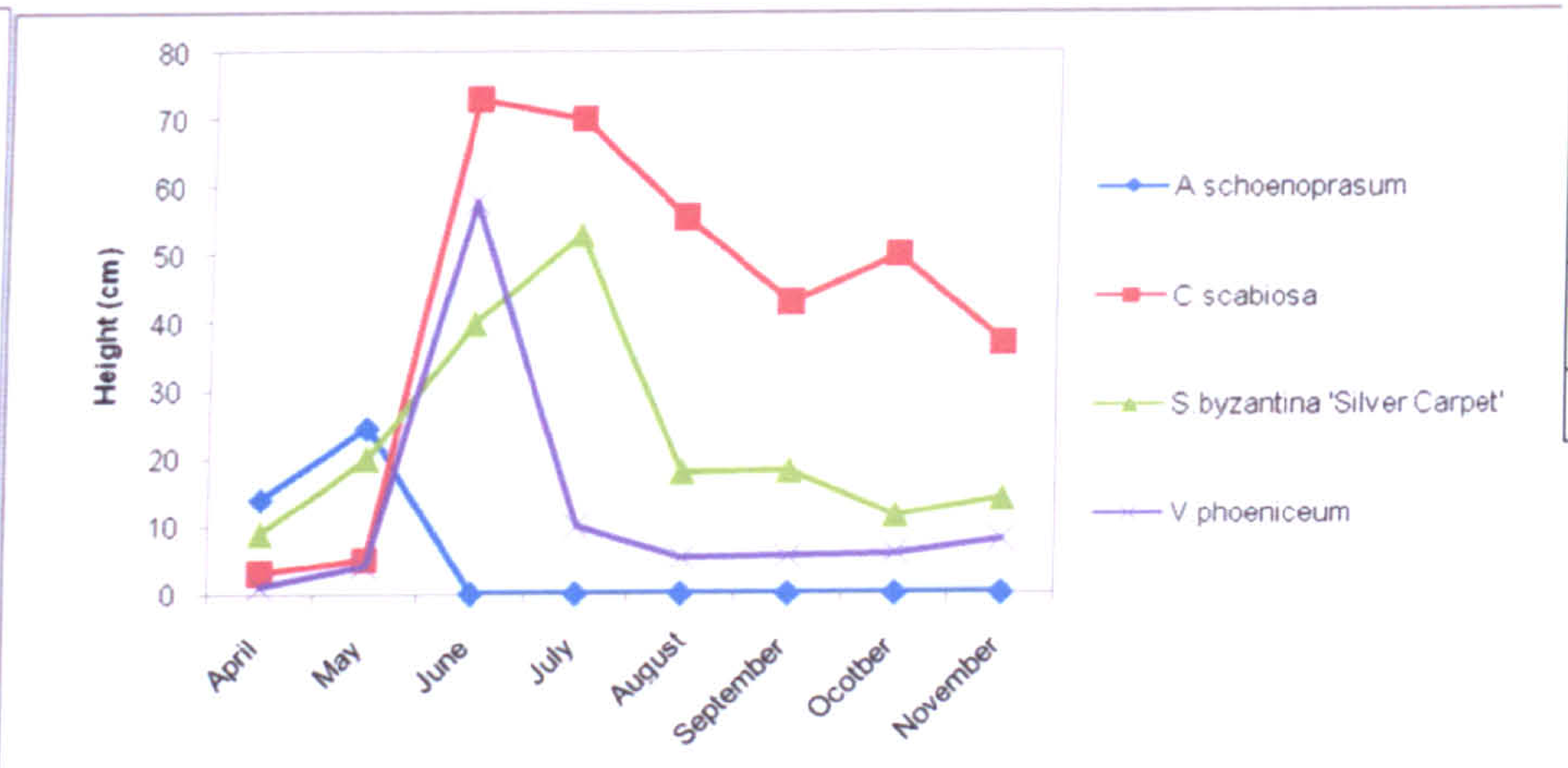


	Growth pattern
A. schoenoprasum	5
M. armeniacum	2
P. veris	1
S. acre 'Golden Queen'	1

Quadrat 26 (Low diversity, Low density, Red, SE)

February	March	April	May	June	July	August	September	October	November
									
Flower succession									
A. schoenoprasum									
C. scabiosa									
S .byzantina 'Silver Carpet'									
V. phoeniceum									

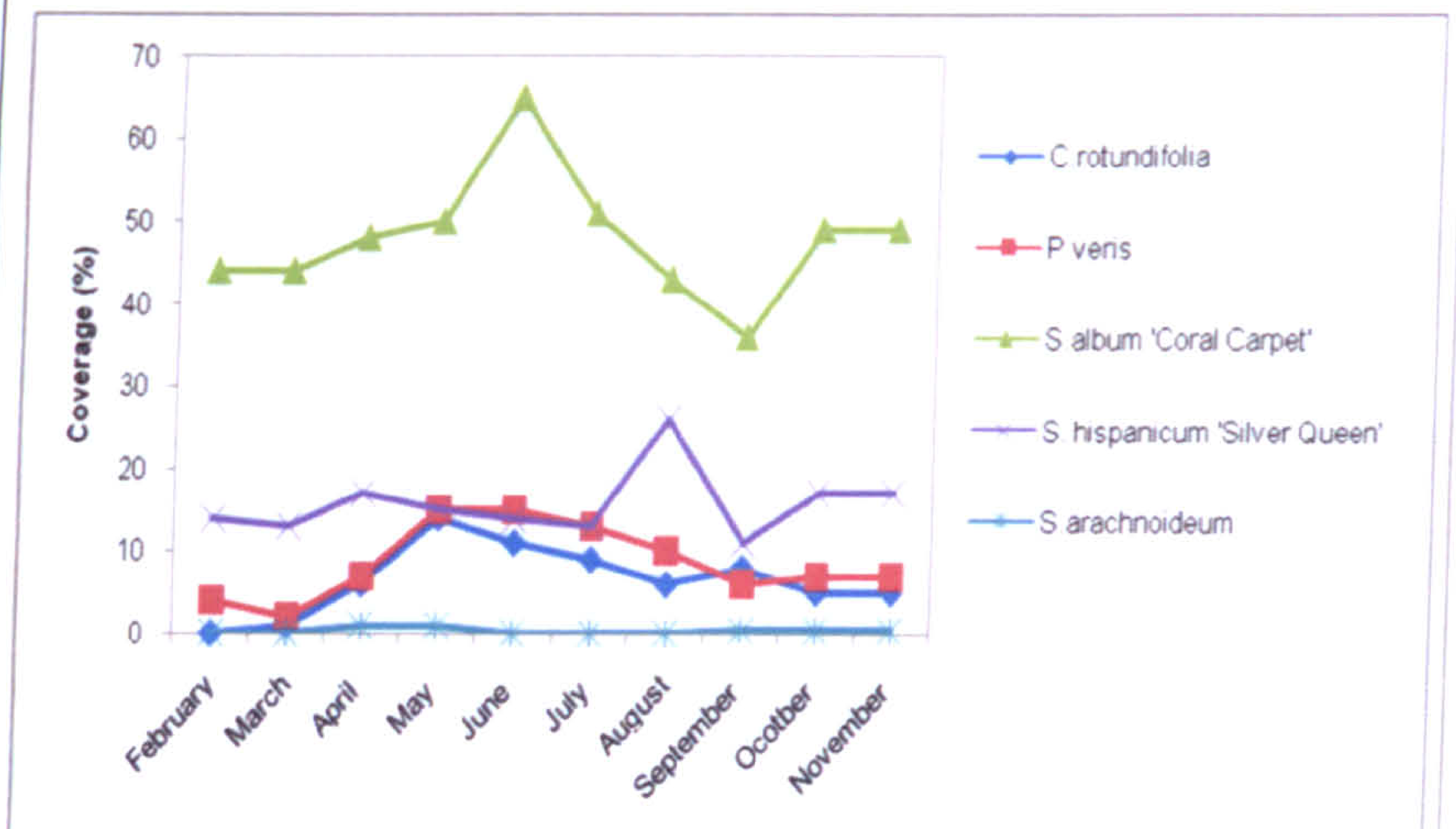


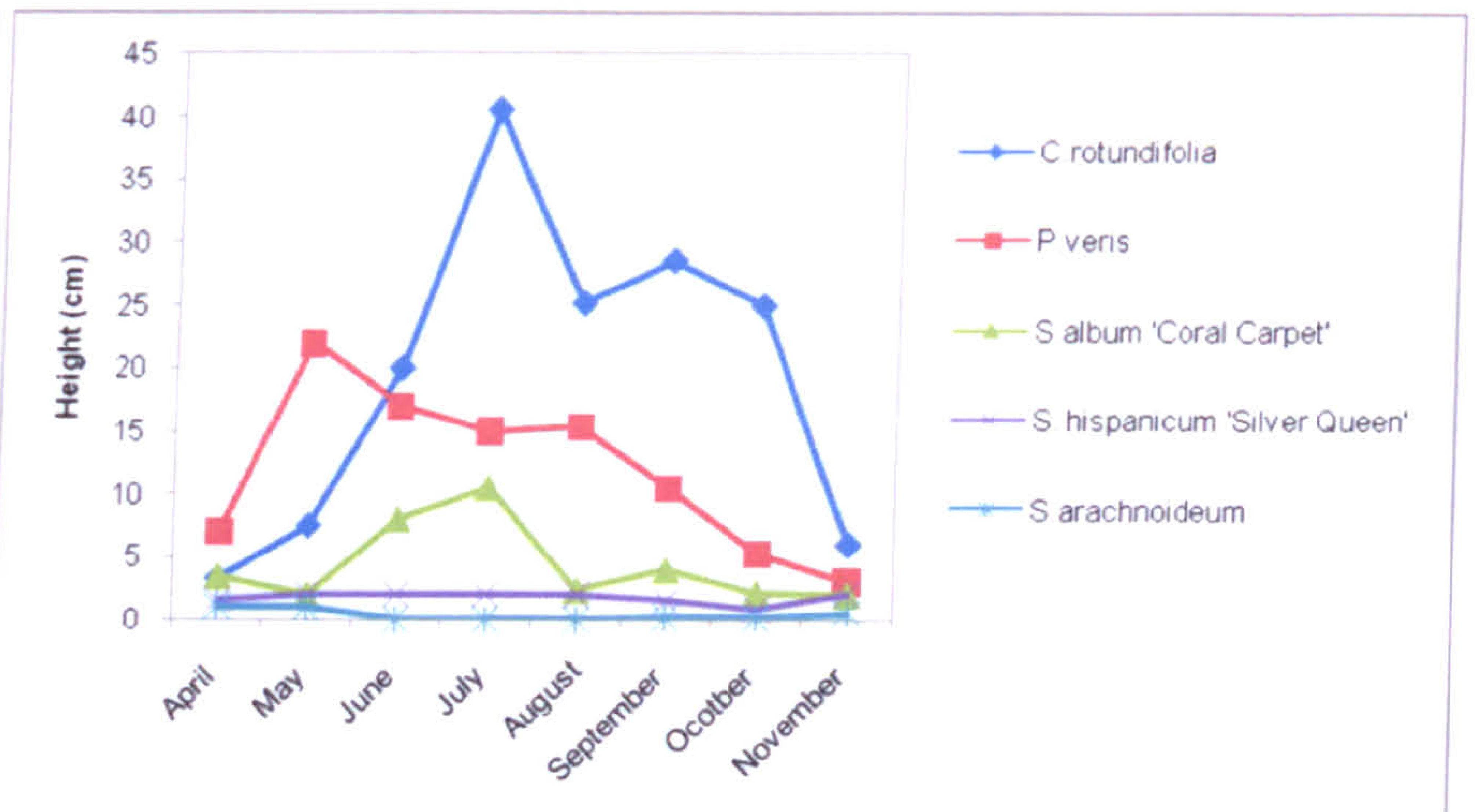


	Growth pattern
A. schoenoprasum	5
C. scabiosa	3
S. byzantina 'Silver Carpet'	5
V. phoeniceum	3

Quadrat 27 (Low diversity, High density, White, SE)

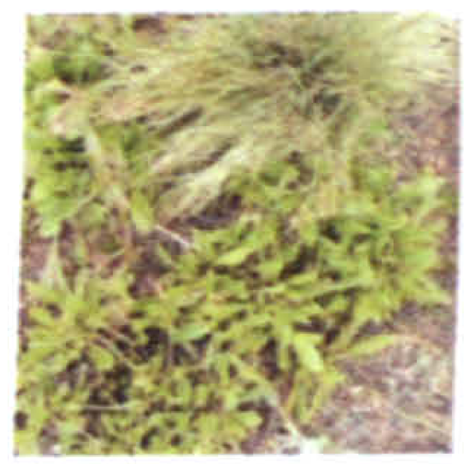
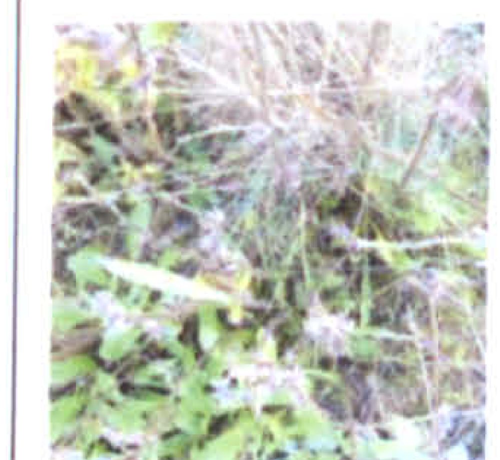
February	March	April	May	June	July	August	September	October	November
									
Flower succession									
C .rotundifolia									
P. veris									
S. album 'Coral Carpet'									
S. hispanicum 'Silver Queen'									
S. arachnoideum									



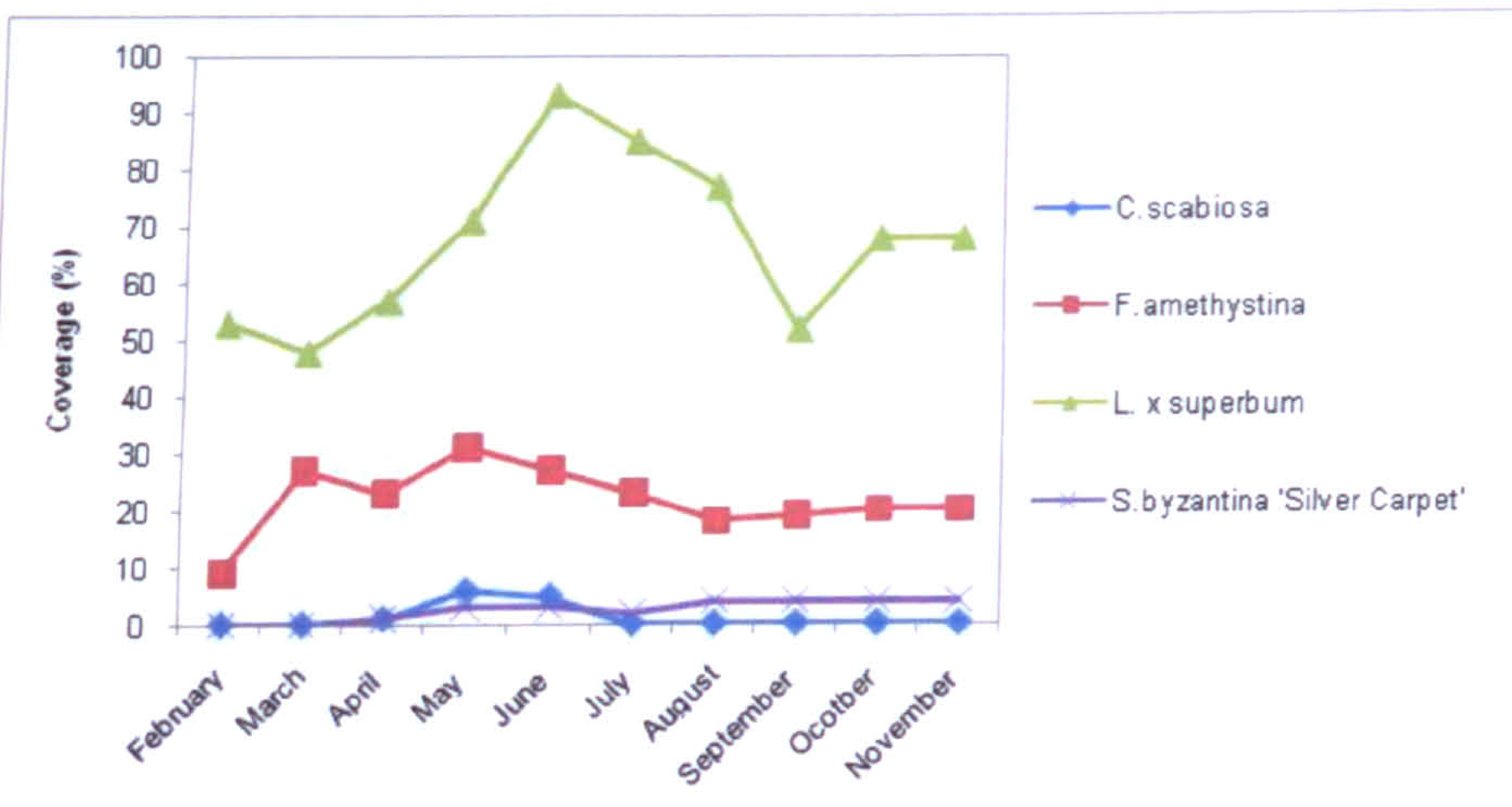


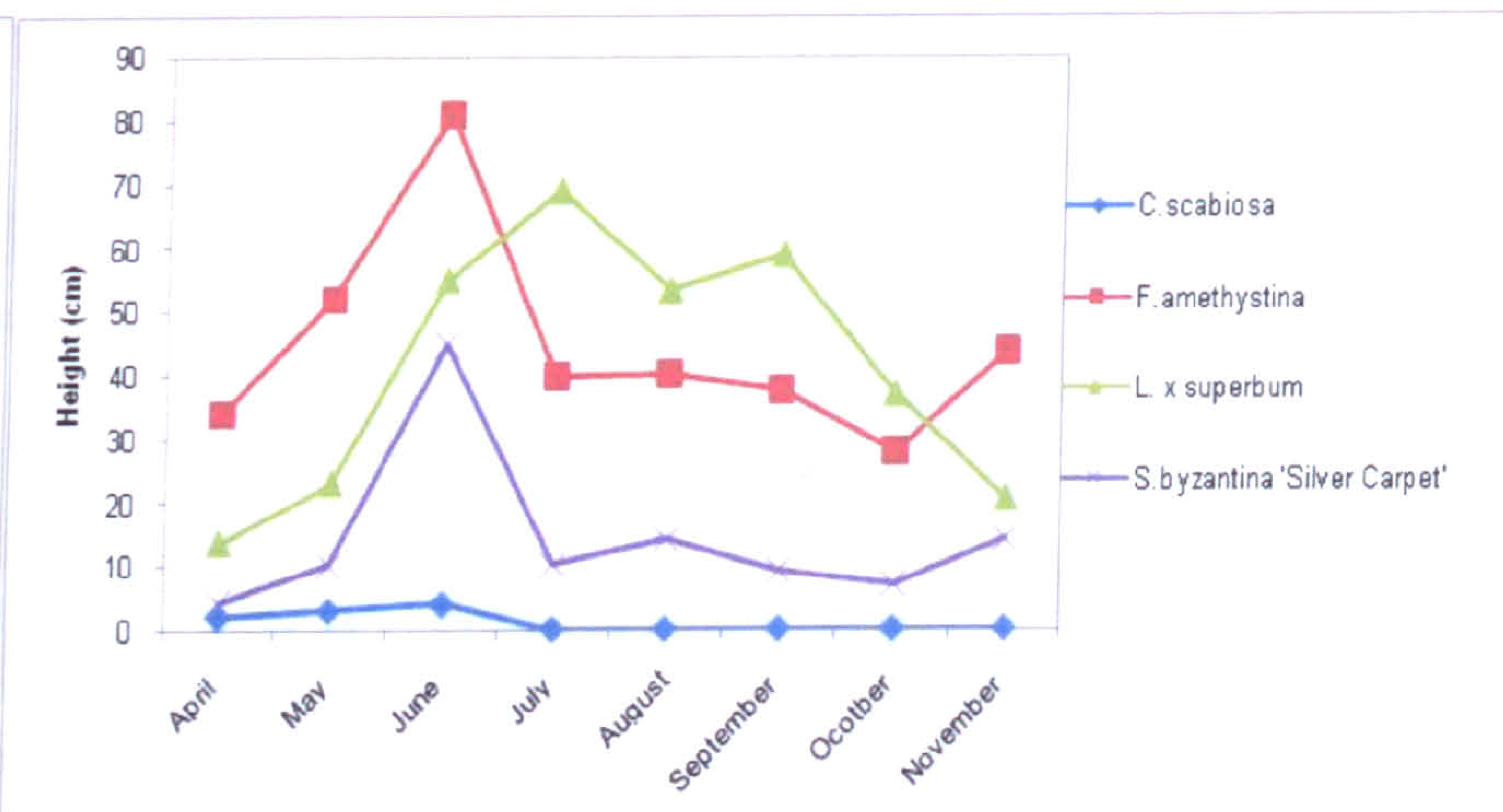
	Growth pattern
C. rotundifolia	2
P. veris	1
S. album 'Coral Carpet'	1
S. hispanicum 'Silver Queen'	1
S. arachnoideum	1

Quadrat 28 (Low diversity, High density, Red, SE)

February	March	April	May	June	July	August	September	October	November
									

Flower succession									
C. scabiosa									
F. amethystina									
L. x superbum									
S. byzantina 'Silver Carpet'									



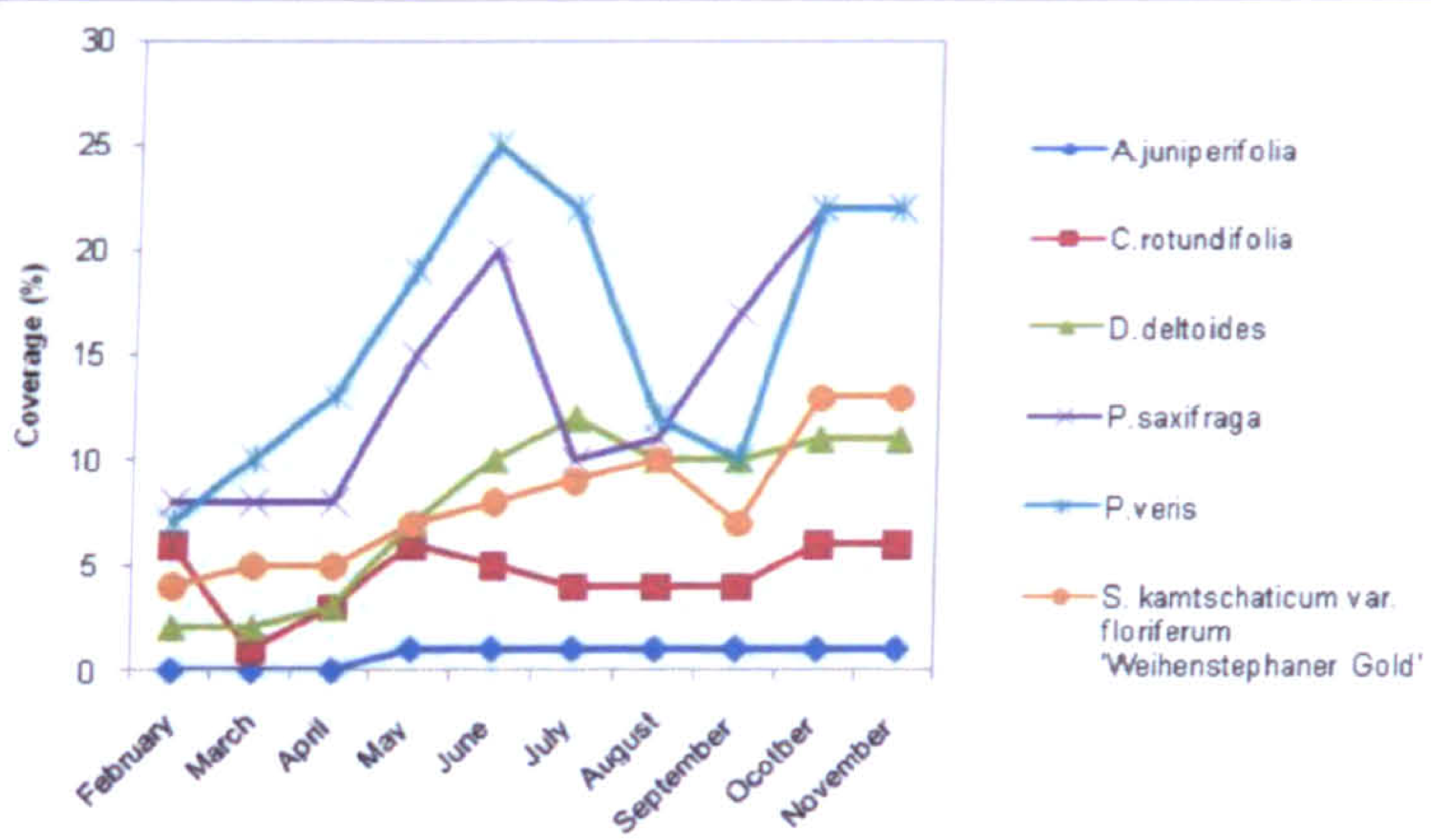


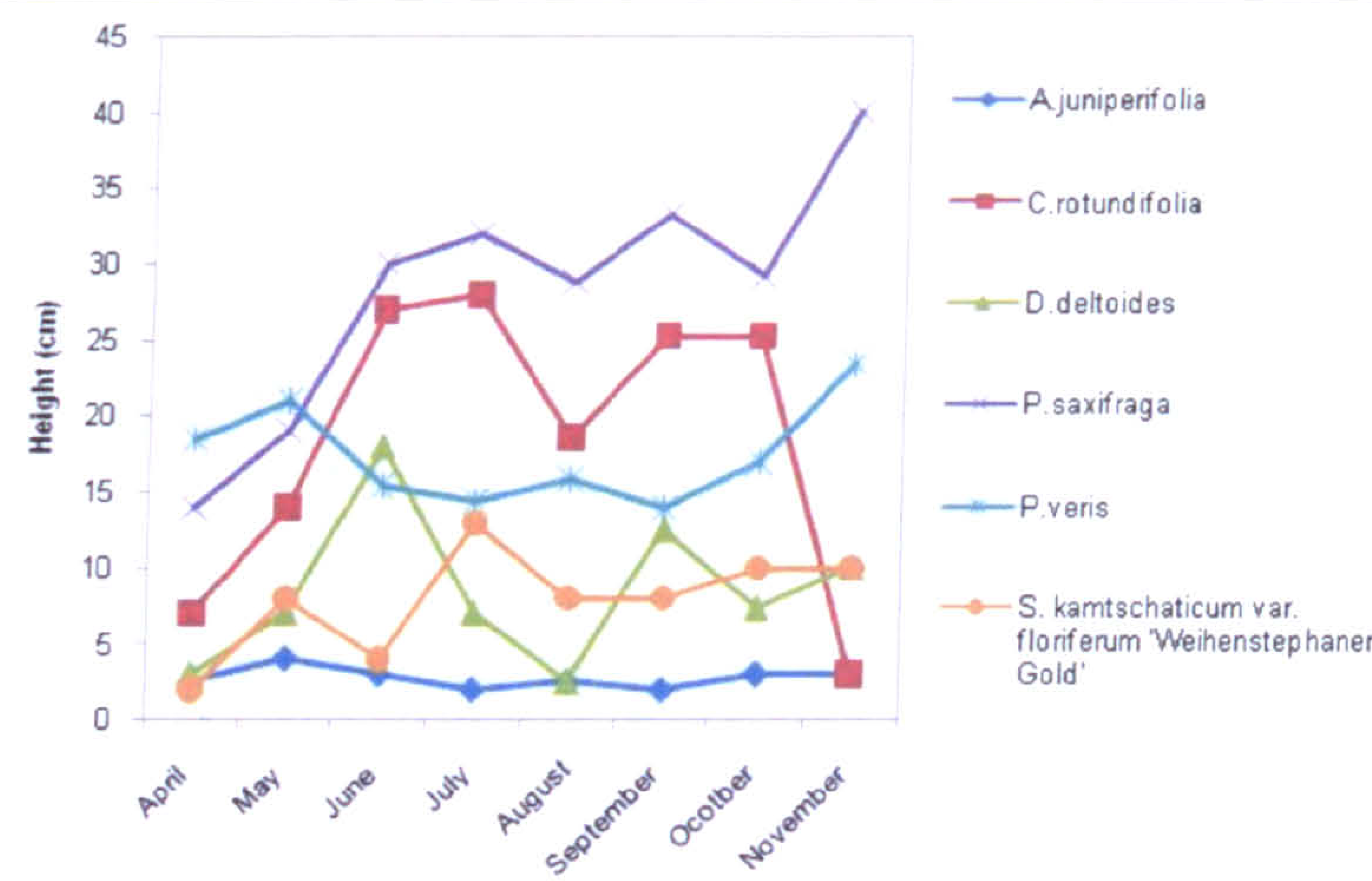
	Growth pattern
C. scabiosa	3
F. amethystina	2
L. x superbum	4
S. byzantina 'Silver Carpet'	5

Quadrat 29 (High diversity, Low density, White, SE)

February	March	April	May	June	July	August	September	October	November

Flower succession	February	March	April	May	June	July	August	September	October	November
A. juniperifolia				■						
C. rotundifolia					■	■		■	■	
D. deltoides					■					
P. saxifraga							■	■	■	
P. veris	■	■	■	■					■	■
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'				■	■	■		■	■	■



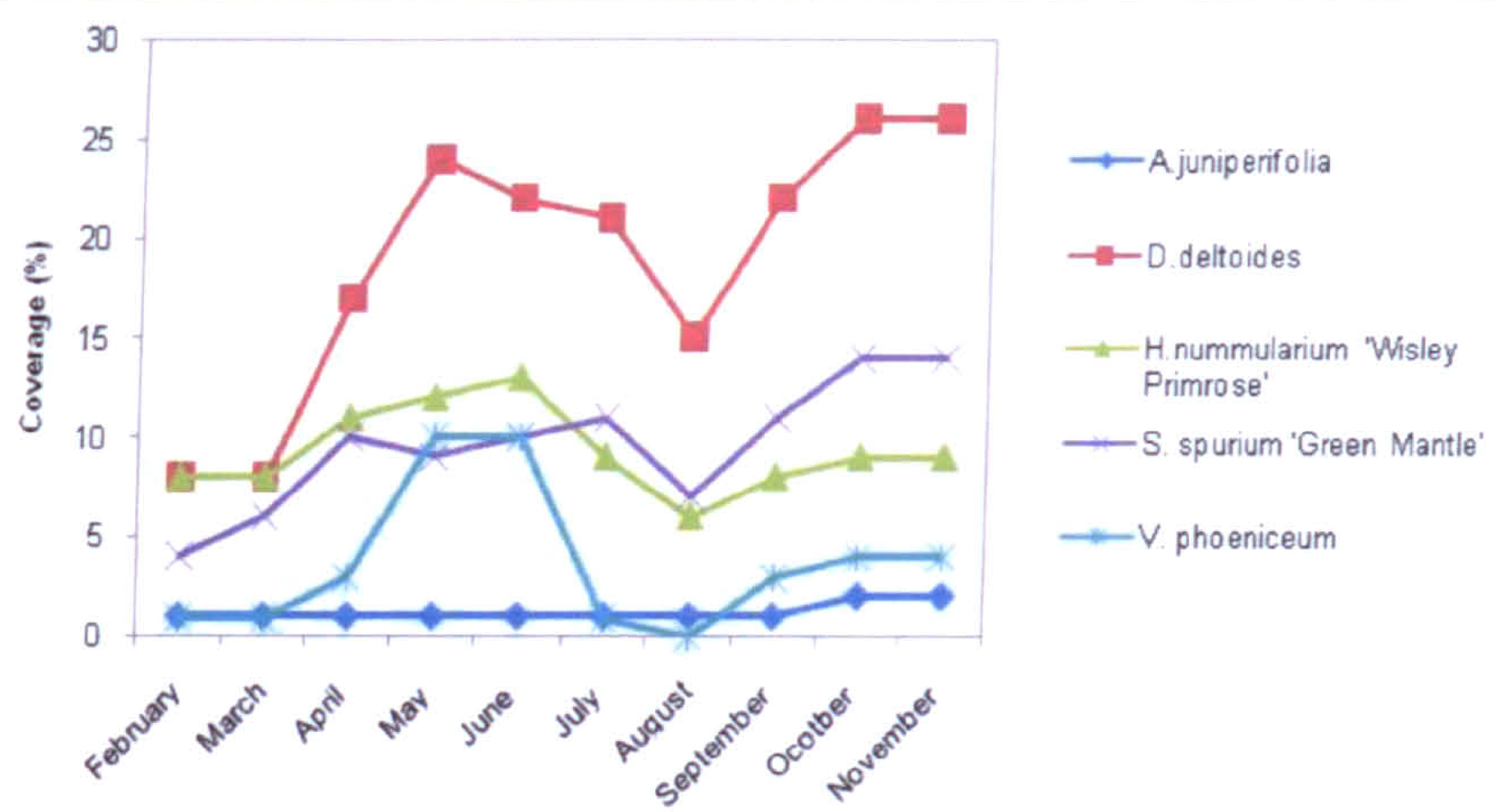


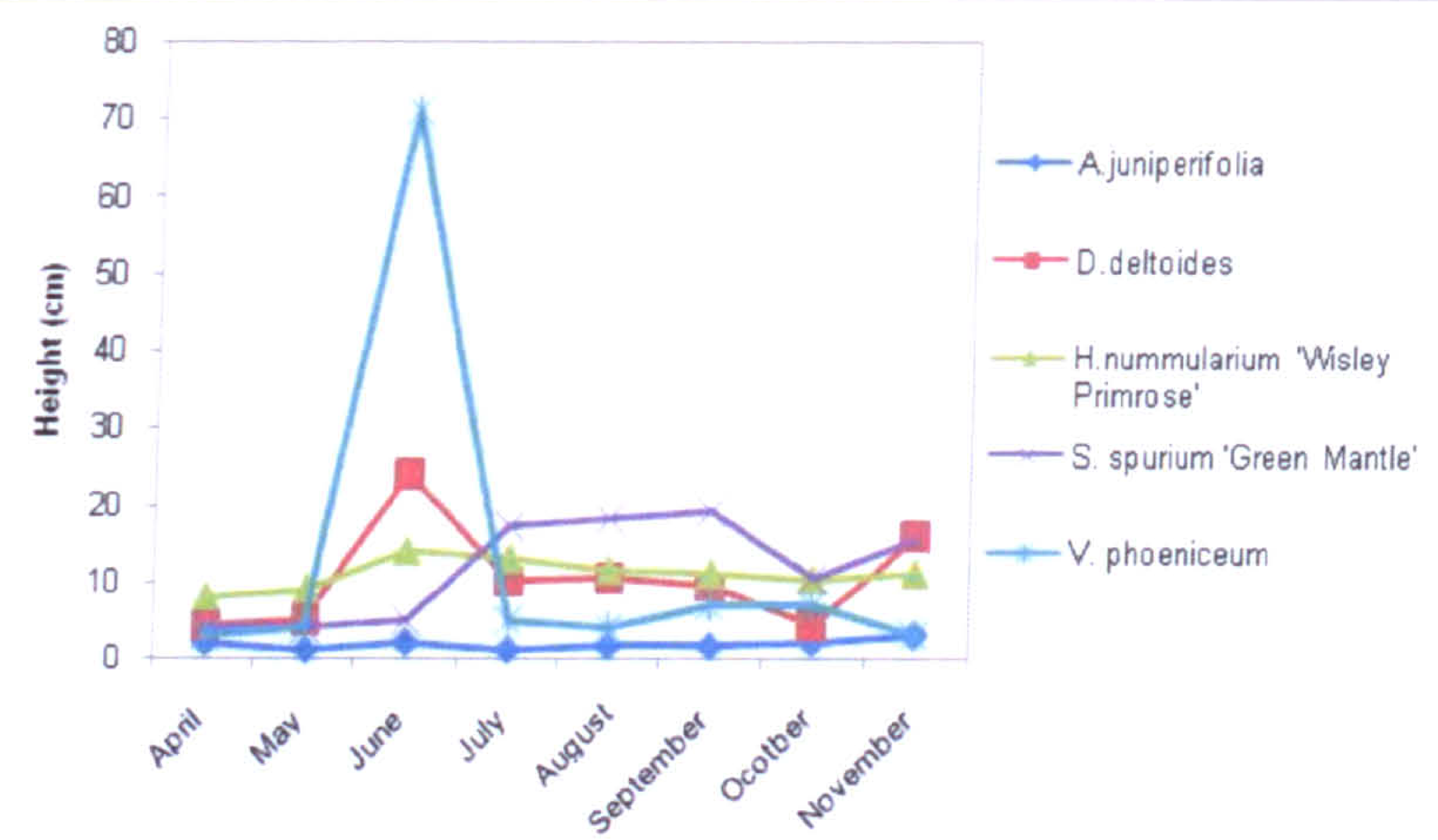
	Growth pattern
A. juniperifolia	1
C. rotundifolia	2
D. deltoides	2
P. saxifraga	6
P. veris	1
S. kamtschaticum var. *floriferum* 'Weihenstephaner Gold'	1

Quadrat 30(High diversity, Low density, Red, SE)

February	March	April	May	June	July	August	September	October	November

Flower succession										
A. juniperifolia	No flower									
D. deltoides										
H. nummularium 'Wisley Primrose'										
S. spurium 'Green Mantle'		No flower								
V. phoeniceum										

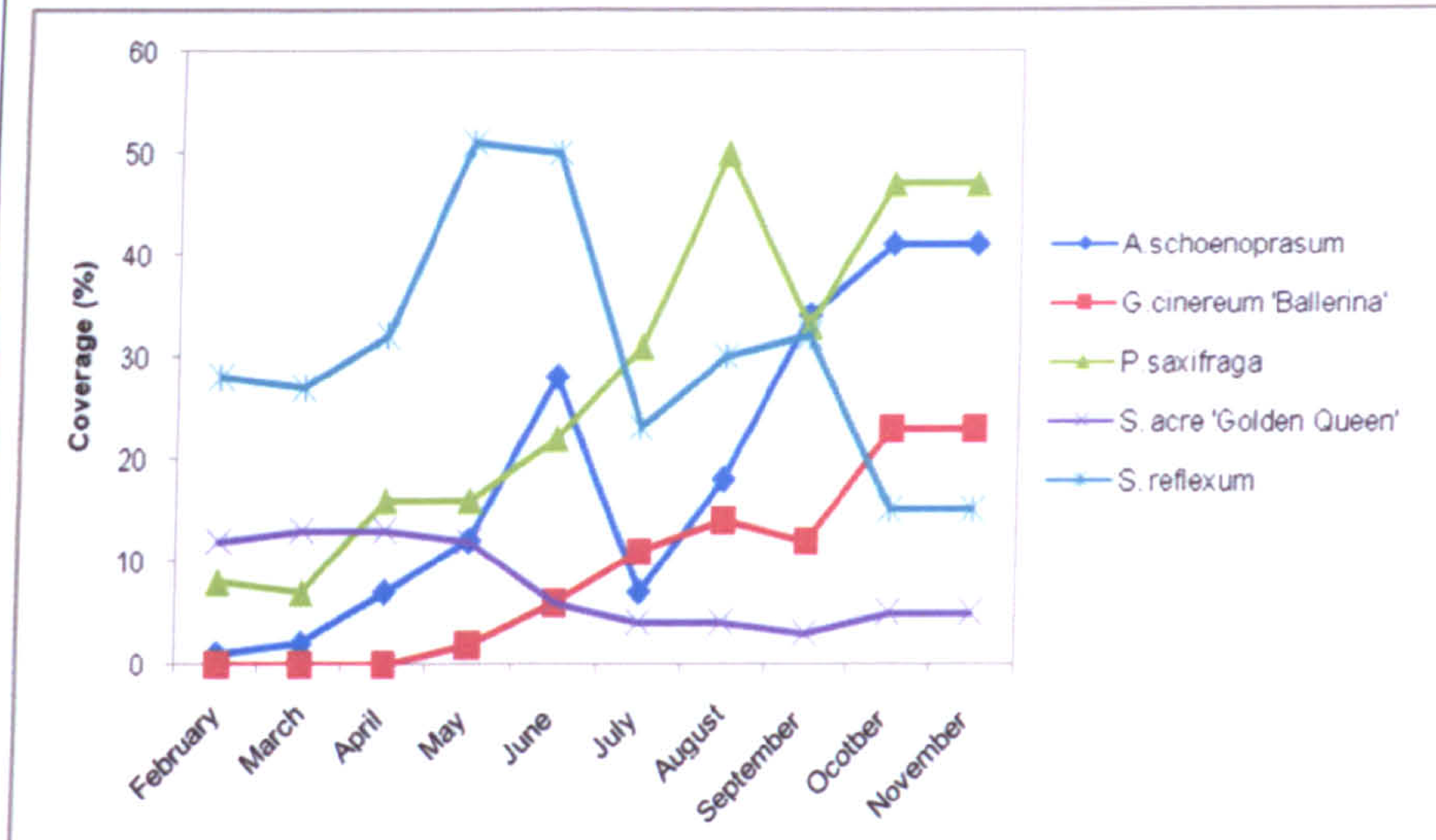


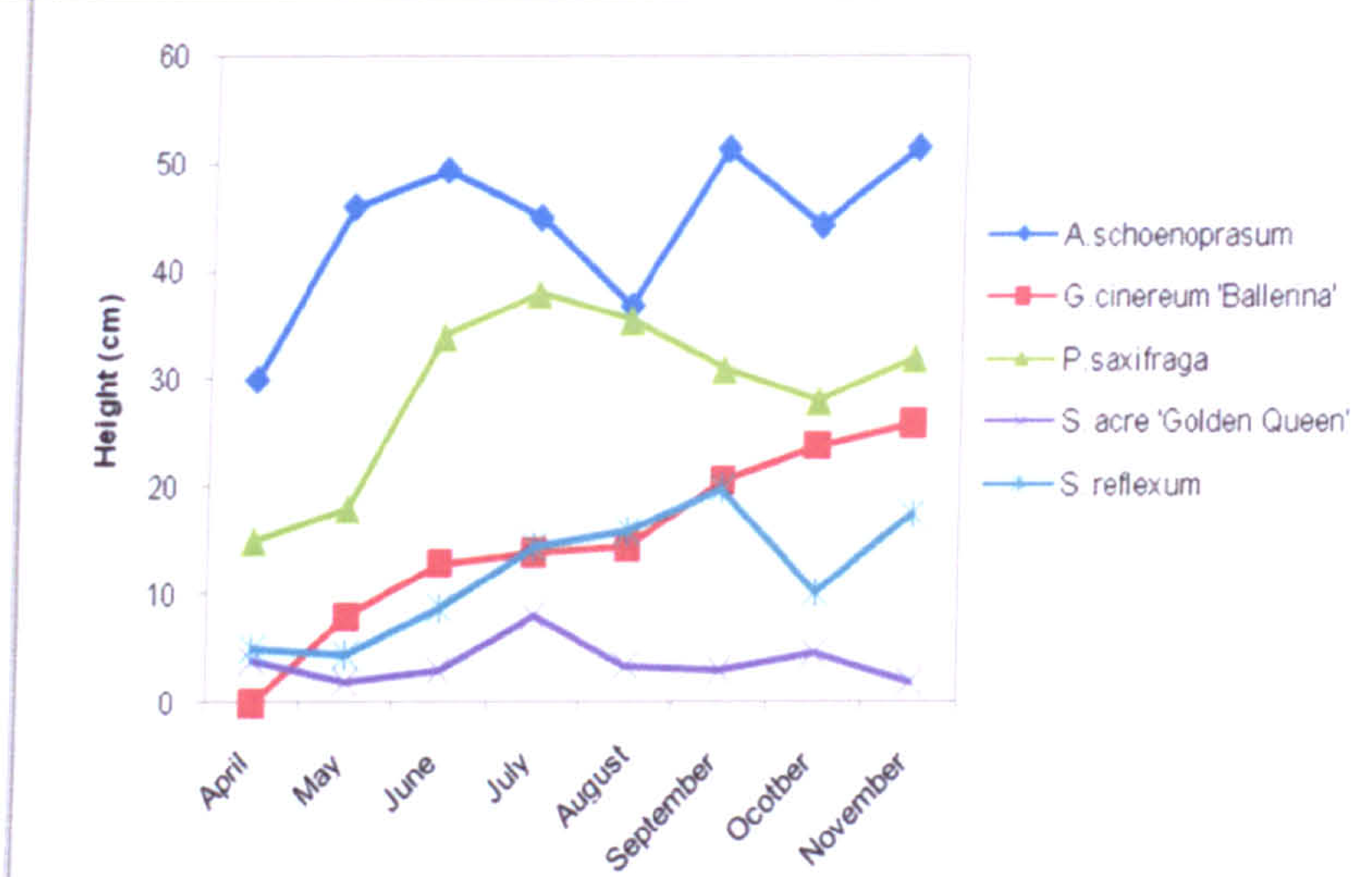


	Growth pattern
A. juniperifolia	1
D. deltoides	2
H. nummularium 'Wisley Primrose'	1
S. spurium 'Green Mantle'	1
V. phoeniceum	3

Quadrat 31(High diversity, High density, White, SE)

February	March	April	May	June	July	August	September	October	November
									
Flower succession									
A. schoenoprasum									
G. cinereum 'Ballerina'									
P. saxifraga									
S. acre 'Golden Queen'		No flower							
S. reflexum		No flower							



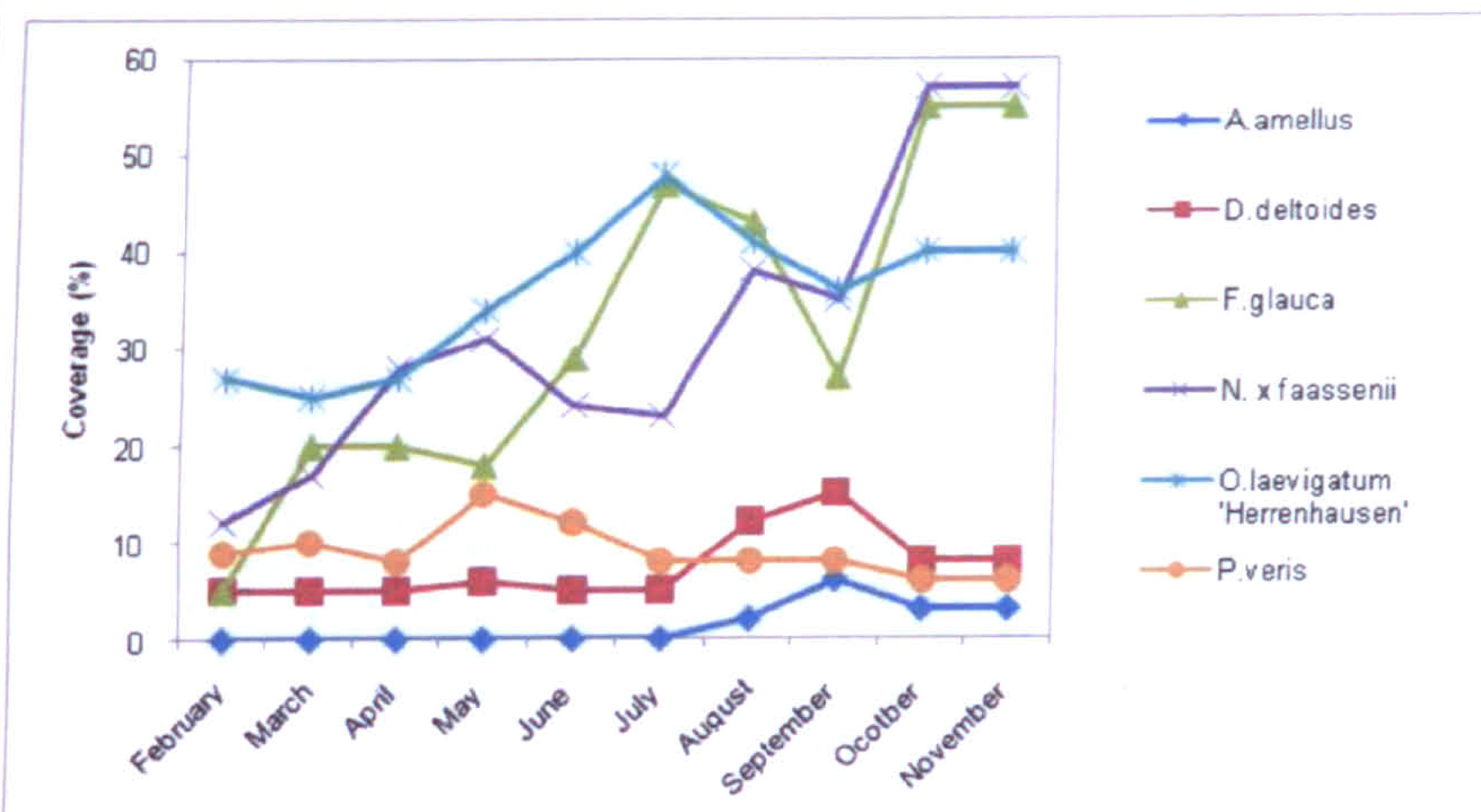


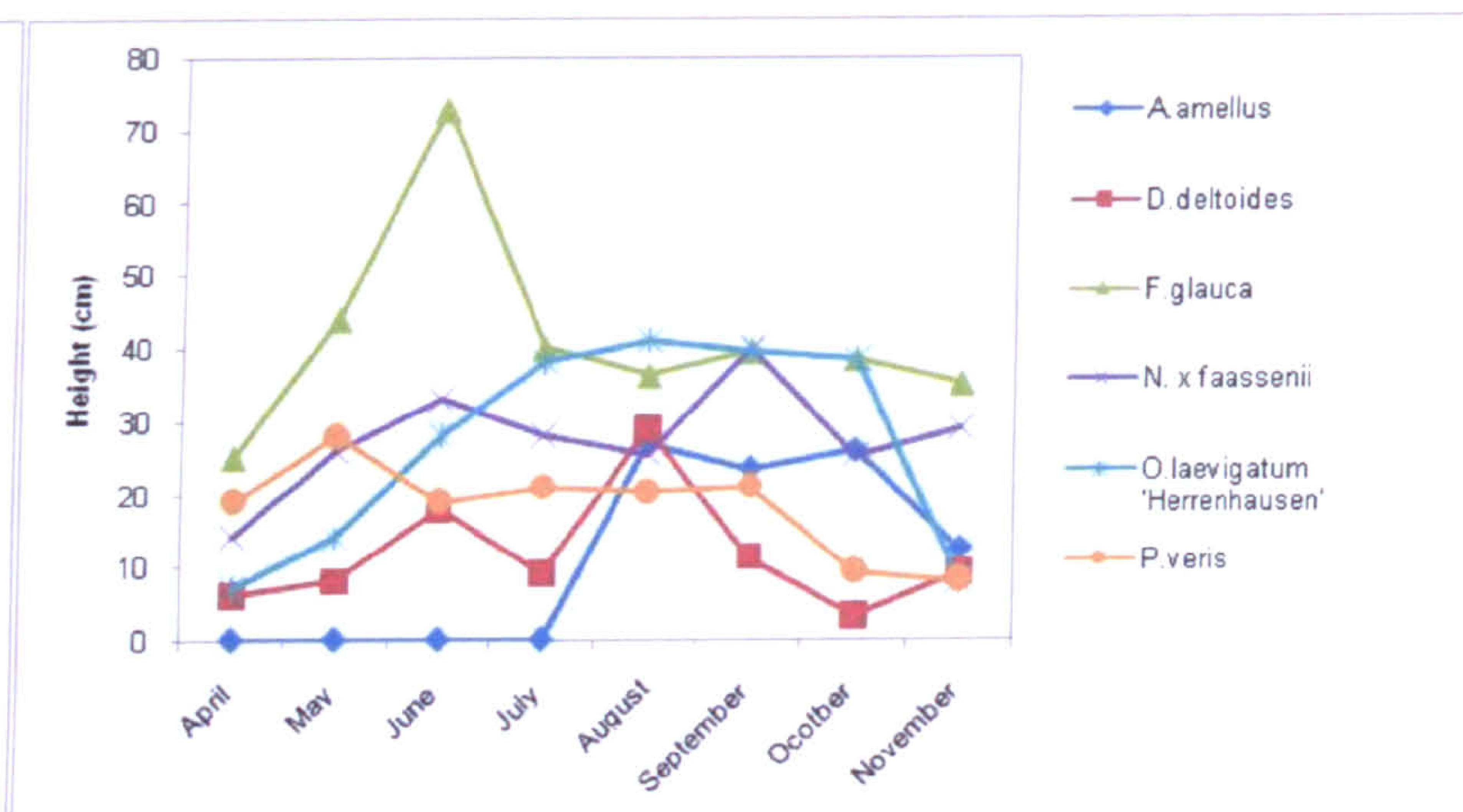
	Growth pattern
A. schoenoprasum	5
G. cinereum 'Ballerina'	2
P. saxifraga	6
S. acre 'Golden Queen'	1
S. reflexum	1

Quadrat 32 (High diversity, High density, Red, SE)

February	March	April	May	June	July	August	September	October	November

Flower succession										
A. amellus										
D. deltoides	No flower									
F. glauca										
N. x faassenii										
O. laevigatum 'Herrenhausen'										
P. veris										





	Growth pattern
A. amellus	2
D. deltoides	2
F. glauca	3
N. x faassenii	5
O. laevigatum 'Herrenhausen'	4
P. veris	1

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