The Development of a Smart Irrigation Control System for Living Wall System

By

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ABSTRACT

Most recent studies of Living Wall Systems (LWS) have emphasized their benefits in terms of aesthetics, improving urban vegetation cover and thermal benefits. However, few have focused on the plant water consumption and irrigation management. LWS often use a fixed irrigation period (e.g., 5 min/day) rather than designed based on actual plant requirements and their adaptation to water availability. The aim of this research was to investigate the potential of irrigation controllers that regulated water availability more precisely, and determine how plants respond. Maximum growth is not always desirable in LWS as this relates to greater maintenance (and hence costs) with trimming and pruning requirements. Thus, the research investigated if drier irrigation regimes could control excessive plant growth whilst maintaining quality. Differential irrigation regimes ('wet', 'medium' and 'dry') were set up to determine their effect on growth, leaf number and aesthetic quality. Comparisons were made across two different climates (Jingmen, China and Sheffield, UK) and at different phases of the annual growth cycle. Four taxa (*Hosta*, *Vinca, Heuchera* and *Hedera*) were included in the study, with plant communities being composed of single species or mixed species combinations in a LWS cell unit. Results showed that plant growth and quality was determined by the irrigation treatments. It was feasible to control growth and retain respectable plant quality, although optimum regimes for this could vary with time, species and location. Experiments with single species per cell, suggested overall the best regime for Sheffield was a medium irrigation treatment (from 40% to 65% soil moisture content) during May-June followed by a wet treatment (from 65% to 90% soil moisture content) during July-October. For Jingmen, a medium to wet treatment during May to June and a medium treatment during July to Oct was considered the best compromise. Drier regimes however, were considered better when plant species were mixed together, with dry treatment (from 15% to 40% soil moisture content) during May to June and the medium treatment during July to August being recommended for both Sheffield and Jingmen. Some LWS systems are subjected to heavy shade. A small sub-experiment explored the relationship between shading and irrigation level. Based on the treatments imposed shade seemed to have a greater impact on growth than irrigation level, but further research is required to find critical levels of shading and how that implicates plant water use. The author developed a model for controlling irrigation in a mixed species LWS and an original framework for a smart irrigation control system has been provided within the thesis.

Keywords:

Irrigation Design, **Maintenance**, **Plant growth**, **Living Wall System**.

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CHAPTER 1: INTRODUCTION TO GREEN WALL SYSTEM

1.1 BACKGROUND

The term green infrastructure (GI) was coined to counterbalance the ideas of built or grey infrastructure, and promotes the contribution vegetation and natural systems / processes provide to human society usually in an urban context, viz urban green infrastructure (Benedict and McMahon, 2002; Gill et al., 2007; Tzoulas et al., 2007; Cameron and Blanuša, 2016). The term infrastructure implies there are different components and connections between these components. These terms have become commonplace since the 1980s (Rusche et al., 2019). Discussion of GI have promoted the development of methods within ecology, ecological planning, and landscape ecology, as well as promoting he concept of biological corridors and ecological networks that aim at the protection of biological and ecological systems (Luan et al., 2017). The cotemporary idea of GI has settled on the interconnected green space networks that comprises of various open spaces and natural areas, including greenways, wetlands, parks, street trees and local nature reserves. These elements form an interconnected and unified network system (Wu et al., 2020). Benefiting from the concept of GI, reintroducing green plants into densely populated urban areas and connecting them with existing green spaces has become the simplest and economical used method for governments in many countries to counteract the urban fragmentation of the natural environment (Cameron et al., 2014; Luan et al., 2017).

Green walls (GW) are one component of trying to re-establish vegetated connections across a cityscape, and provide a living mantle to the buildings they are constructed on. The core competence of vertical greening technologies (i.e. Green Walls) lies in its effective utilization of the building surfaces that are otherwise left unoccupied (Yuri, 2016). With the development of cities, the urban population continues to rise, and the green area per capita continues to decline. Traditional urban vegetation, such as the street trees and the public open green spaces, are often contested by more commercial land uses (Dunnett and Kingsbury, 2008). The Green Walls solve this problem by using the previously neglected building surfaces, a new dimension is exploited, giving more spaces for plants. Such capacity has gained the status for the Green Walls as an important constituent of urban GI (Wolf, 2012; Cameron et al., 2014). Two forms of green wall commonly exist – plants grown with roots in the soil or containers at ground level and allowed to grow up a wall (Green Facades - GF) and plants grown in modules attached to the wall in some manner, and usually reliant on artificially provided irrigation (living walls - LW).

The concept of Green Walls can be traced back to a long history, such as the Hanging Gardens of Babylon in Western and the City Wall of Suzhou in Spring and Autumn Period in Eastern (Köhler, 2008; He, 2013; Wood et al., 2014). Abundant studies have found that Green Walls can improve many aspects of the urban environment, the benefits including a reduced urban heat island effect (Parizotto and Lamberts, 2011), reducing air pollution (Srbinovska et al., 2021), improved storm water attenuations (Loh, 2008), habitats and food resources for the wildlife (Darlington, 1981), an increased biological diversity (Mayrand and Clergeau, 2018), and enhanced amenity values (Hedblom et al., 2019), etc. More development history and benefits details are discussed in the next chapter.

In light of the fact that vegetation on buildings (green walls and roofs) can partially mitigate for loss of green space at ground level, a number of city authorities have formulated relevant incentive policies, and in some case even mandatory measures (Design for London, 2008). Berlin in Germany, promotes vertical and roof greening through financial incentives and mandatory regulations. The concept of "Biotope Area Factor (BAF)" was first introduced, which weighted different forms of green spaces for their ecological effectiveness (Ngan, 2004). Linz, Tokyo, Cologne, Portland, Toronto are other examples of cities implementing policies or financial incentives for environmental benefits. There are incentives for private development of green walls and roofs etc. and companies can apply for grants to help with installation costs (Grant, 2006; Lawlor et al., 2006; Design for London, 2008). Similarly, Beijing has established policies to enhance ‘off-ground’ city greening, with the 2008 Olympic Games acting as a trigger. As part of the combined efforts to improve the air quality, Beijing set a target of greening 30% of its high-rise buildings and 60% of the lower buildings (Grant, 2006).

Due to policies adopted by different countries, a rise in the number of the Green Walls projects is evident, and the accumulated area has been observed in many pioneering cities. Such GWs are now found across the world, including typical indoor and outdoor GWs project s such as Edmonton International Airport (Canada), Changi International Airport (Singapore) and Mumbai International Airport (India) (Hindle, 2012).

In recent years, the number of studies on Green Walls has also increased (Köhler, 2008; Suzuki, 2008). The most widely discussed topics are "Analysis of Economic Cost of Plant Green Walls", "Analysis of Thermal Impact on Buildings", and "Analysis of Species Suitable for Vertical Green Walls". One limitation of the existing studies is that there has been limited discussion around the maintenance of Green Walls, especially the irrigation strategies. The ecosystem services from green walls come from the living plants and associated growing media, and healthy plants require appropriate, well-maintained irrigation. The role of irrigation level and plant development remains understudied but effective irrigation is required to provide:

1) Benefits for the environment. Water is essential for all life. With the increasing uncertainty in the global environment, water resources per capita are decreasing. At the same time, cities are facing the accelerating loss of water resource, increased problems with water pollution hampering development, and on the other hand, they are troubled by the accumulation of rainwater in irregular and extreme events (Lau and Mah, 2018). Therefore, optimizing the irrigation management of LWS is vital to improve water conservation, but also to promote the sustainable development of LWS.

2) Ensuring the ecosystem services of Green Walls. At the most basic level well-designed irritation is essential to ensure survival and normal growth of plants on Green Walls. This allows the plants to provide the range of required benefits (e.g. energy saving, emission reduction in buildings, habitat for wildlife etc). These benefits can be quantified, and the initial high cost can be offset with a clear calculation.

3) Benefits for plants within Green Walls. Understanding the water consumption of plant communities within a Green Wall is beneficial to saving water and formulating the optimal irrigation for plant development. Achieving the optimal irrigation is usually representative of consuming the correct amount of water, which is helpful in keeping plant quality whilst avoiding excessive runoff onto hard surfaces or loss through the drainage system.

4) Benefits due to minimising financial costs. Previous research and experience indicates plant growth can be controlled via irrigation levels (Cameron et al., 2006). Therefore, it is possible to slow down the growth rate of plants on Green Walls through designed irrigation strategies, so that can not only extent the life cycle of Green Walls (i.e. keeping plant alive) but also significantly reducing the maintenance cost associated with pruning and plant replacement.

5) Benefits for Green Walls research. The research on the irrigation of the Green Walls can also serve as a research template for other Green Walls maintenance technologies.

1.2 RESEARCH AIMS

The Green Walls technologies mainly include parts which are Green Facades and Living Wall Systems (LWS) (Pérez et al., 2011; Perini et al., 2013; Wood et al., 2014; Manso and Castro-Gomes, 2015; Koch et al., 2020). This thesis focusses on the irrigation system based on LWS and the main aim is:

To enhance the performance of LWS by developing a smart irrigation control system

This research addresses the research aim by targeting two objectives:

- To determine what irrigation is required to keep plants alive and aesthetically pleasing, but not encouraging excessive shoot growth
- To determine if a number of plant species can be grown to these requirements using the same irrigation.

1.3 POTENTIAL RESEARCH CONTRIBUTIONS

The new smart system is designed to enable distanced monitoring and control of irrigation that are triggered automatically by itself, taking into account the plant growth stage, current substrate moisture status and other environment information. It is obvious that this system can save water and labour cost. Accuracy is improved by the use of sensors to measure the growing media parameters, including soil moisture, air temperature, air humidity, pressure and rain water. This is based on the knowledge of the growing media's water holding capacity and different plant species' water requirements and their response. Water will be provided to the LWS according to data combined from the temperature, soil moisture and rain sensors. This helps to reduce water consumption and regulate the growth rate of plants. Apart from decreasing resources waste, this system also enables less frequent manual maintenance. By using ZigBee technology, the system is fully wirelessly-connected, automated and remotely-controlled, which further reduces the labour cost by reducing the frequency of manual work, and finally realize decrease in the LWS cost drastically. This system can provide a sustainable method that works for a long term for automatic smart irrigation control for LWS, and offer a new aspect for developing landscape smart maintenance system.

1.4 THE CONCEPT AND DEVELOPMENT OF GREEN WALLS

1.4.1 The Definition and Development of Green Walls (GWs)

1.4.1.1 The definition of Green Walls

The original concept of vertical vegetation, including a wide use of green walls, is that plants grown on vaulted terraces were allowed to climb up / hang down the walls of the terraces (Köhler, 2008; Wood et al., 2014; Manso and Castro-Gomes, 2015). Green Walls (GWs) today can be defined as vegetation growing up or placed on a wall, and which may have functions such as providing; an aesthetic vertical surface, shade to a building wall, shelter to buildings from prevailing winds and a place to grow food (Köhler, 2008; Wood et al., 2014).

Since the industrial revolution with the subsequent and the intense process of urbanization, there has been a trend to remove green space and replace it with buildings (Wendel, 2011; Zhou and Chen, 2018). Green walls are seen as an antidote to this process and can facilitate a degree of urban 're-greening' without sacrificing building space, i.e., GWs use little horizontal space. Vertical greening is used to make the most of the building façade and has become popular in recent decades. The definition of GWs covers any form of green vertical mantle, although there are sub-divisions (see below). The technology involved can be very simple or very complex, with at one extreme climbing plant species (i.e., vines) being allowed to grow naturally up a vertical wall surface, and at the other extreme plants contained within modules with irrigation and nutrition levels controlled by sophisticated sensors and computer control. Green walls are both an environmental or landscape phenomenon, but also a novel planting technology utilising 'ecological material' for the landscape and architecture industries.

1.4.1.2 The development of modern Green Walls

The theoretical system of the GWs cannot be simply attributed to certain individual, project or construction. Instead, it has been developed by the resultant force from multiple social aspects. More attention is also paid to GWs' ecological function, which contributes to urban sustainable development.

Green Walls have experienced a long developmental history and have been applied widely across different cultures. They not only benefit human economically, but also provide aesthetic appeal and give spiritual comfort. According to Köhler (2008), Wood et al. (2014) and Sadeghian (2016), the increasing popularity of GWs is closely related to the cultivation technology of climbing plants, which can be traced back to the primitive agriculture era. Climbing plants have been used by the Babylonian civilisation, through the Greek and Roman empires and brought to Western countries where traditional green walls are still utilised (Fig 1.1). Various traditional technologies of green walls have been developed in the Western world. In the Mediterranean areas, vines were gradually developed and exploited to cover pavilions and provide a degree of cooling and shade in this hot climate. The Romans planted grapes (*Vitis vinifera*) under the trellis of gardens and the walls of villas (FLL, 2008). From the 17th and 18th centuries on, the UK and Central Europe have seen a surge in using climbing plants mostly with the purpose of covering building walls. The gardens and castles covered with vines became the symbols of the secret gardens in this period. At that time, the form of vertical greening technology was relatively simple, which was based on the traditional pot planting and manual irrigation (Newton et al., 2007). In other situations, green walls would be 'self-generating' in that common climbing plants such as ivy (*Hedera helix*) would germinate and grown towards a wall and up it to gain more light. In this way, many medieval buildings would have a natural façade of self-generating plants (Wood et al., 2014).

In northern parts of Europe, many countries have a tradition of using vegetation on buildings as a material for facade or roof, where sod (turf) was a common option (that is a layer of top-soil mixed with grass and roots). For the Vikings of Scandinavia, turf was used to cover facades and roofs in order to insulate their houses against the extremely cold weather outside (Fig 1.2). In the United States and Canada, a similar style for building with walls being built with several layers of sod, was found in Northern Midwest prairies. Yet despite the thermal insulation, sod was not an ideal structural material due to the fact that the sod-covered walls could be easily damaged by water from rain and melting snow. So it was not an ideal structural material, and needed frequent replacing. This is the reason why sod houses don't have much archaeological presence in this region (Wood et al., 2014). In Europe and North American in the 19th century buildings envelope was often decorated with woody climbers (Dunnett and Kingsbury, 2008; Manso and Castro-Gomes, 2015).

Figure 1.1 The simulating of Hanging Gardens of Babylon about green walls (Wood et al., 2014, p. 14)

Figure 1.2 Icelandic turf houses (Wood et al., 2014, p. 14)

Green walls also have a tradition of use in China. The construction of the green wall can be traced back to the construction of the city wall in Suzhou. In the construction of the City Wall of Suzhou, King Wu Fuchai ordered that the plant of Bi Li (*Ficus pumila* Linn.) be used to ornament it in Spring and Autumn period (771 B.C. – 465 B.C.) (Shi and Niu, 2011; He, 2013). Later during the ‘Five Dynasties and Ten Kingdoms’ period (907 A.D. – 979 A.D.), Meng Chang, the emperor of Later Shu, ordered the planting of *Hibiscus* spp. over the walls of Chengdu to achieve a uniform greening effect (Zhang, 2004). In addition, although the Suzhou classical gardens have been rebuilt and repaired many times, the vertical greening is still preserved in these gardens. For example, self-climbing plants such as *Hedera helix* (Ivy) and *Jasminum nudiflorum* (Winter jasmine) are encouraged to climb and grow over stones in courtyard, the use of which emphasizes the integration between spirit and nature, an important philosophy of Chinese traditional garden culture (He, 2013; Chen, 2014).

In the late 19th century, the Garden City Movement evolved, being considered the symbol for integrating greening into city planning. This movement in 1920s in Britain and North America pushed the development of modern green walls, where green landscape was cultivated to promote the combination of gardens and residences. As a result, green corridors and trellis with self-climbing plants on them developed well in this period. Short after this, the first investigations concerning green walls were conducted from a botanical point of view (Köhler, 2008). Later the early 20th century witnessed the German Jugendstil movement (Art Nouveau) that also aimed to take the house and the garden as an organic whole. This movement bred some incentive programs that were launched to promote installing green walls. In the 1980s, green walls appeared as a new idea to improve environment and ecological integrity of cities. As a matter of fact, Berlin is representative of those programs. From 1983 to 1997, Berlin witnessed the installation of nearly 245,584 m^2 of green walls (Köhler, 2008).

An advocate of this green movement was Patrick Blanc, known for his large number of GWs projects around the world during and after the 1980s (Grant, 2006; Bakar et al., 2013; Manso and Castro-Gomes, 2015; Zaid et al., 2018). In 1988, Patrick Blanc, a French botany researcher from the French National Research Institute (Centre national de la recherche scientifique (CNRS)) invented the “Green Wall” technology which uses the felt non-woven fabric and timing water supply system (Gandy, 2010). This invention is based on his studies of tropical epiphytes where he observed that many plants can survive without soil as long as enough water supply is ensured. In the early 1990s, wire, cable, rope net system and modular grid panel system entered the market in North American. In 1993, the largest artificial green wall at that time was built with a grid panel system at the Universal CityWalk Hollywood at California, United States (Yang, 2014). Green walls were not restricted to outdoor locations, and providing enough irradiance (light) can be provided green walls lend themselves to interior design too. In 1994, the Canada Life Building in Toronto, Canada, utilized a biofiltration system to build indoor living green walls (Jain and Janakiram, 2016). In 2004, Patrick Blanc cooperated with Jean Nouvel to build the first vertical garden over the walls of the Administrative building of the Quai Branly Museum in Paris, which led the trend of living green walls around the world (Gandy, 2010). In 2017, GRHC (Green Roofs for Healthy Cities) launched the Green Wall Design 101 in North American. In 2008, GRHC set up the Green Great Wall Award Fund for development of the green walls (Yang, 2014). Such modern GWs can be found across the world, including typical indoor and outdoor GWs projects such as Edmonton International Airport (Canada), Changi International Airport (Singapore) and Mumbai International Airport (India) (Hindle, 2012).

The research and application of the modern GWs started late in China, with research only starting in the 1980s (Tang, 2017). Most early research focused on the selection of plant species based on the traditional vertical greening. This relied on balcony greening, trellis greening and self-climbing plants. The GWs technologies, at this time, were mainly focused on how to place the vegetations which originally from the horizontal in the ground soil into the vertical spatial, but they lacked the research on the relationship and influence between them and their structures (e.g., buildings). Researches were mainly published in the journals of garden and landscape (Tang, 2017). In recent years, with the development of computer-based control system, architecture and materials science, vertical greening is being diversified and technology-driven. Since 21th century, architects began to combine the GWs design with architecture design, not only for the aesthetic requirements from customers but also for benefits brought by energy saving and sustainable development. And an increase in research on GWs published in Chinese academic journals was noticed. Although GWs have gained attention from the academic research, the GWs in China are mainly applied in projects concerning vertical greening development and construction in megacities like Beijing, Shanghai, Shenzhen and Hong Kong (Wu, 2012; Yang, 2014).

In Beijing urban areas, various plants were selected to be planted in the street walls, roofs and overpasses to promote the development of urban GWs. Nearly 500 projects were constructed before 2008 (He, 2013). Those projects made their contributions to the increasing urban greening. In 2010, Beijing Times reported that Beijing was planning to green the roofs and walls of public buildings, which aimed to create more green space via using the empty space around and between buildings. In February same year, Wuhan put into use the fruits of "Greening houses, trees in overpasses" projects. The car parking building of the Yellow Crane Tower is the largest ecological GWs in Wuhan, covering areas of 1.63 x 10000 m2 (Zhang, 2018) . It uses the light GWs technology same as that used in the French Pavilion at Shanghai Word Expo. The Haishan GWs project in Chongqing applied an advanced and convenient GWs method where fine-tuning GWs panels in the ground can help to achieve the best plant status (Zhang, 2018). The development of GWs in Shanghai is relatively fast for China, judging by the number of GWs projects and the number of new GW forms. The Shanghai Greening Technical Specification published by Shanghai Government lays down the details for applying GWs in Shanghai, and in turn is promoting further GWs in Shanghai. In addition, the ecological importance of GWs was noted in Shanghai, and this has helped disseminate GWs technology wider within China, e.g. the technology module used to build green walls of the China Pavilion, Baosteel Grand Stage and other pavilions (Zhang, 2011; Wu, 2012; He, 2013).

In the past two decades, rapidly increasing population and far-reaching urbanization has resulted in China erecting significantly more tall buildings. Allied with this trend, ideas centring on making buildings greener have sprung up. This includes positive examples of the "Eco Skyscraper ", "Bioclimatic Skyscraper" or "Vertical Landscape" (Yeang and Richards, 2007), with such buildings trying to strike a balance between natural environment and built infrastructure. The idea of "Vertical Farming" is to use the skyscrapers as the space for the cultivation of plants and animals (Despommier, 2010). The "Sky Garden" or "Sky Atria" is designed to make the building's social and public spaces green (Pomeroy, 2013). While the "Landscaped Facade" aims to cover the facades of buildings with vegetation (Wood et al., 2014).

1.4.1.3 The classification of modern Green Walls

Considering that the research on the modern GWs has varies different classification, and in order to avoid unnecessary confusion in this research, it is necessary for the author to introduce the terms of GWs in this research.

Research on Green Walls technologies have used may special terms such as: "vertical garden" (Peck et al., 1999; Bass and Baskaran, 2003), "vertical greening systems" (Perini et al., 2011), "green vertical systems" (Pérez et al., 2011) or "vertical greenery systems (VGSs)" (Wong et al., 2010). However, the term 'Green Walls (or GWs)' uses in this thesis to respect for all green wall technologies unless otherwise specified.

Often the specific classification of GWs and how they have been defined by researchers relate to 1) the basis of the support structures used, 2) the different plants selected and 3) the method of application. (Dunnett and Kingsbury, 2008; Kontoleon and Eumorfopoulou, 2010; Manso and Castro-Gomes, 2015; Natarajan et al., 2015) (Table 1.1).

Table 1.1 Examples of finer-grained classifications on the GWs by different researchers (Pérez et al., 2011; Perini et al., 2013; Wood et al., 2014; Manso and Castro-Gomes, 2015; Koch et al., 2020)

AUTHOR(S)	MAIN CLASSIFICATION	SUB-CLASSIFICATION	DETAILS
Pérez et al. (2011)	Green facades	Traditional green facades	
		Double-skin green facade or green curtain	Modular trellis
			Wired
			Mesh
		Perimeter flowerpots	
	Living walls	Panels	
		Geotextile felt	
Perini et al. (2013)	Green façades	Direct greening system	
		Indirect greening system	Indirect greening system
			Indirect greening system combined with planter boxes
	Living wall systems (LWS)	LWS based on planter boxes	
		LWS based on foam substrate	
		LWS based on felt layers	
Wood et al. (2014)	Facades-Supported Green Walls	Metal Mesh Green Wall	
		Cable-Supported Green Wall	
		Rigid Green Wall	
	Living Walls	Vegetated Mat Living Wall	
		Hanging Pocket Living Wall	
		Modular Living Wall	
Manso and Castro-Gomes (2015)	Green facades	Direct	Traditional green facades
		Indirect	Continuous guides
			Modular trellis
	Living walls	Continuous	Lightweight screens
		Modular	Trays
			Vessels
			Planter tiles
			Flexible bags
Koch et al. (2020)	Green facades	Direct systems	
		Indirect Systems	
	Living walls systems (LWS)	Inert Substrate (stone wool, lava granules, textile) Hydroculture	Thick (e.g. rockwool)
			Thin (e.g. textile)

		Organic substrate (potting soil, peat moss)	Thick (e.g. basket, planter, gutters)
			Thin (e.g. foil, textile with plant bags)

Research from the above authors use the same name of the main classification for the GWs (i.e., Green Facades and LWS) but based on different methods. Pérez et al. (2011) propose that the key to distinguishing between Green Facades and LWS resides in whether the support structure and covering direction of the GWs are variable. For Green Facades, they emphasize on its nature as a simple support structure that supports climbing plants or hanging plants to cover the required area in a directional manner. Perini et al. (2013) propose to distinguish between the Green Facades and the LWS based on whether the nutrition and the watering systems are needed. Wood et al. (2014) propose that the employment of the growing media is what distinguishes the LWS from the Green facades. They think that Green facades should not have planting media. Koch et al. (2020) distinguish between LWS and Green Facades based on whether the plants grow in the soil on the ground: the former does while the latter does not.

The sub classifications from authors about these two main types of GWs are similar on the Green Facades but different on the LWS. The further sub-division of Green Facades depends on the height of the plant in the space and whether it directly touches the building surface (Pérez et al., 2011; Perini et al., 2013; Manso and Castro-Gomes, 2015; Koch et al., 2020). However, in terms of the LWS, the definition for the LWS from Pérez et al. (2011) is relatively vague, since they simply refer to the system as constructed with panels and/ or geotextiles that felt over the surface, which, importantly, could support more plant species. Perini et al. (2013) propose that the sub-classification are defined according to the different forms of the containers, while the Wood et al. (2014) are made according to the types of the plants' containers. The definition from Manso and Castro-Gomes (2015) also relies on the morphological characteristics of the basis containers. The major contribution of their work is the simpler and more intuitive terms labelled for that the LWS sub-categories. Koch et al. (2020) sharply sub-classified into two categories, with the growing media provide organic nutrients for one category but not for the other.

Based on the above review, it is then concluded that the classifications of Green Facades all follow the same logic, but the detailed ways of expression could be different. Another literature review find is that the technological progress of Green Facades is relatively slow, which is reflected by the fact that later studies tend to give more discussions on LWS but not on the Green Facades.

Based on previous literature review, the details on Green Facades are quite similar in all researchers as it is a relatively traditional technology. While, the sub-classification of LWS is relatively complex as most of standard of classification based the categorizations of containers. New terms about LWS classification appears in the new research is mainly to express the emerging new types of containers of LWS. Since the aim of this research is not focused the classification of LWS, author generates a simply GWs classifications (Table 1.2) based on the characterise of containers which similar as previous classification rules for readers.

Table 1.2 The classification of Green Wall

	CLASSIFICATION	SUB-CLASSIFICATION	DETAILS
Green walls	Green façades	Direct	Traditional green facades
		Indirect	Continuous panel trellises
			Modular trellises
	Living wall system	Continuous	Lightweight plane
		Modular	Trays
			Container
			Flexible bags

Green facades have developed well, where hanging or climbing plants that are attached to a wall are used as the core element (Dunnett and Kingsbury, 2008). They can be divided into "direct" and "indirect" types by their working mechanism (Manso and Castro-Gomes, 2015). Direct green facades mean plants' roots are fixed in the earth directly, thus facilitating climbing directly to the wall. Indirect green façades, on the other hand, include two types of supporting structures: modular trellises and continuous panel trellises. Continuous panel trellises provide a supporting structure such as stainless trellis that can help to guide plant growth. Modular trellises have very similar solutions but the biggest difference is that the modular trellises have a container for the plants (Fig 1.3).

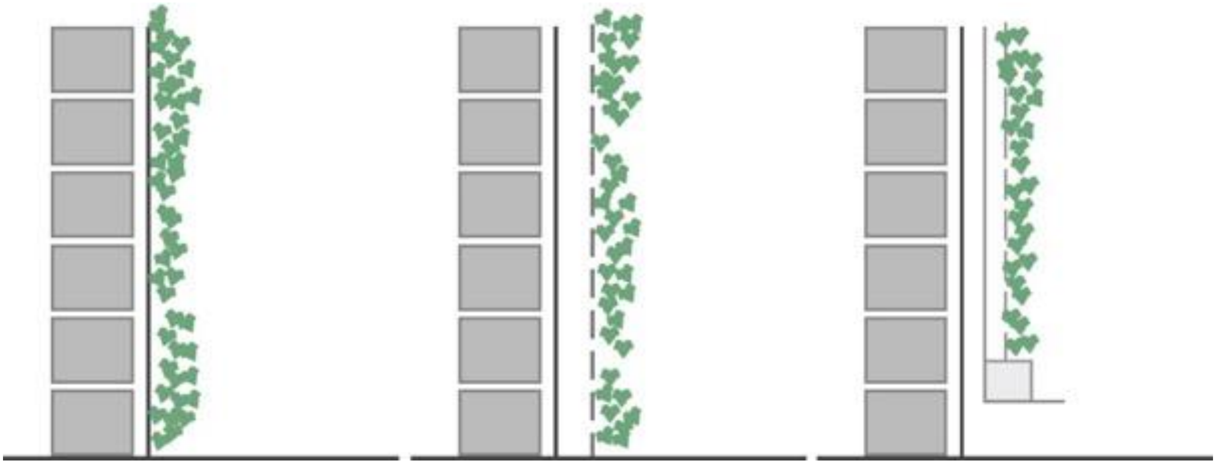

Figure 1.3 Traditional green facades (left), Continuous panel trellises (middle), and Modular trellises (right)

Living walls (LWS) are recent innovations in greening systems for the building surfaces. Unlike green façades, LWS consist of supporting structures, irrigation systems, and growing media. The different types of equipment mean that many options are available when it comes to choosing the proper structure to support a variety of plant to grow on the vertical surface.

Living walls can be classified into the “continuous LWS” and the “modular LWS” based on their application methods (Loh, 2008) (Table 1.2).

Continuous LWS or the “vertical gardens” are first used in “Vertical Garden” by Blanc and reported in 1994 (Manso and Castro-Gomes, 2015). This type of LWS requires no soil and the plants can grow in a fabric layer, such as geotextiles. Owing to hydroponic technologies, in continuous LWS plants are able to get nutrients from the irrigation. But the use of continuous LWS faces two main problems: plant replacement and virus infection (Irwin, 2015).

The main feature of modular LWS is the use of different containers in order to provide space for the plants to grow. Despite its higher costs compared with other green wall technologies, modular LWS presents its own advantage on the circumstances that the wall greening process is applied in large areas, especially when creating beautiful wall landscape, for the reason that this wall greening technology allows installation of plants after several months of pre-cultivation and the development of aesthetic plant patterns in the module.

Containers used in modular LWS are fourfold mainly: lightweight plane, trays, flexible bags and containers (Fig 1.4). Drip irrigation technology is commonly used in modular LWS to provide water and nutrition for plants.

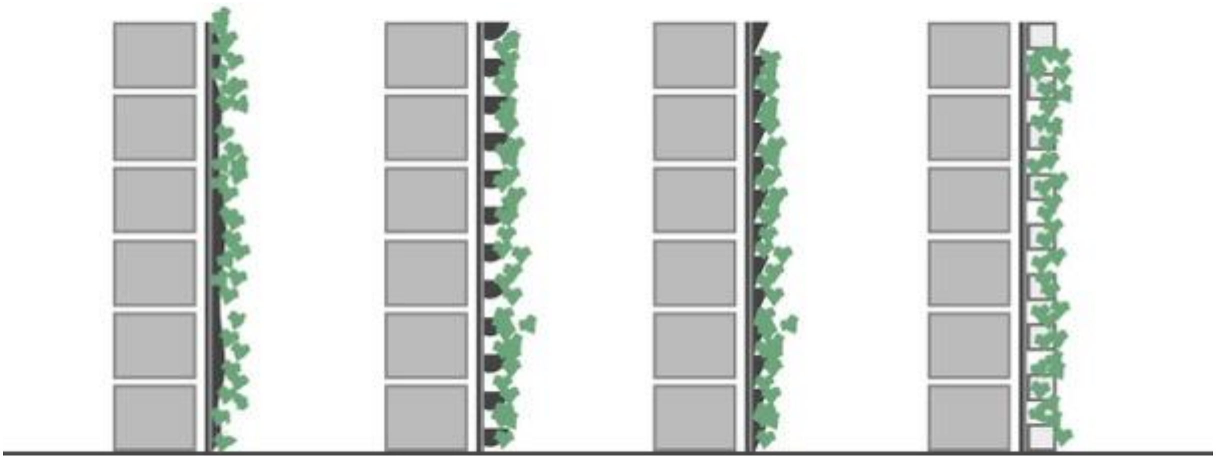

Figure 1.4 Lightweight plane LWS (left), trays LWS (middle left), flexible bags LWS (middle right), and container LWS (right)

1) Lightweight plane LWS. The growing medium is directly set on a lightweight plane system. This system is typified by: the idea that plant patterns can be creatively designed or combined; plants could attach directly to the wall, requiring no extra support from a steel frame, and could be irrigated by running water and rain, leading to the reduction of the construction cost; The system is thin, only 10 cm to 15 cm thick, waterproof and root-blocking, which is conducive to maintaining the building and prolonging its lifespan; Also, it is easy to build and has good overall performance.

2) Trays LWS. Usually, modular trays consist of several interlocked parts. Light-weight materials such as plastic (e.g., polyethylene or polypropylene) or metal sheets (e.g., galvanized or stainless steel, or aluminium) are preferred (Manso and Castro-Gomes, 2015). Each module

usually contains an interlocking system, which is placed on the sides so that they are joined to ensure the continuity of the system. These modular trays also have a front cover, which is used to prevent plants from falling out via the supporting grid that is formed.

3) Flexible bags LWS. A growing media is placed inside flexible bags. Materials used are also light-weight, which enables this kind of LWS to apply vegetation on different forms of surfaces, such as sloped or curved ones. This process begins with paving soft growing carrier such as felt, coconut fibre, non-woven fabric, etc. on the waterproof walls. Afterwards, the bags with the growing materials for plants inside will be sewn in the carrier. For the last step, plants would be put in the bags to achieve wall greening.

4) Containers LWS. The Foundation of this LWS is a frame fixed to the wall. To install it will create a blank space between the surface and the system. This frame can hold the base panel and keeping the wall dry While the base panel provides support to the next layers. Those layers, above the base panel, have flexible, root-proof and permeable screens. pockets are made by cutting the outer layer of the screen so that plants can be grown separately.

Based on rigid rectangular containers full of planting media, Modular living walls are highly attachable to the exterior wall or stand on its own. Made of metal sheets or lightweight plastic, the containers could be shaped according to need, such as wire cages, framed boxes, or solid boxes with pre-cut holes. Sometimes for some particular purposes, the containers are further divided into smaller independent cells and then set vertically or against the wall. Modular living walls could appear in another form, consisting of a number of little sinks or plant pots queued vertically. The soil, natural fibre, or non-organic planting media in containers provide rooting environment for the plants (Wood et al., 2014).

The use of modular containers to plant vegetation is to achieve entire wall greening. Square diamond, circle, and components of other shapes can be lapped or bound together and then fixed to stainless steel or wooden frames - and can thus allow extension across the wall. The spacing and orientation can provide different designs to the plantscapes.

1.5 THE BENEFITS OF GREEN WALLS

Rapid urbanization leaves limited available space for vegetation and any green infrastructure introduced needs to justify itself economically. The GWs not only can increase the greening rate of cities by using vertical space for greening to alleviate the pressure of green space shortage in urban ground, but also can improve the urban infrastructure system. Green walls can be very beneficial, but different factors decide what exact benefits can be enjoyed, such as orientation, building geometry, plant species, geographic location and climate, and green wall components and systems.

Wood et al. (2014) and Manso et al. (2021) in their research points out two kinds of benefits respectively from the perspectives of “urban scale” and “building scale” (Table 1.3). The former refers to the communal benefits in urban area, while the latter alludes to the benefits for the building itself, its users and owners by green walls.

Table 1.3 The benefit of GWs in urban scale and building scale (Wood et al., 2014)

BENEFIT: URBAN SCALE	BENEFIT: BUILDING SCALE
1. Reduction of the urban heat island effect (Castleton et al., 2010; Parizotto and Lamberts, 2011) 2. Reducing air pollution (Srbinovska et al., 2021) 4. Aesthetic Appeal (Hedblom et al., 2019) 5. Psychological Impact on Urban Dwellers (Cameron et al., 2020) 6. Providing Biodiversity and Creating Natural Animal Habitats (Mayrand and Clergeau, 2018) 7. Noise attenuation (Wood et al., 2014) 8. Benefits for stormwater management (Loh, 2008) 9. Reducing light pollution (Wood et al., 2014)	1. Improvement of building energy efficiency and protecting the built façade (Cameron et al., 2014) 2. Agricultural Benefits (Wood et al., 2014) 3. Increasing Property Value (Davis, 2005) 4. Sustainability Rating System Credits (Wood et al., 2014)

1.5.1 The Benefits of Green Wall in Urban Scale

1. Reduction of the urban heat island effect

Caused by the temperature difference between urban centres and country-side, the Urban Heat Island (UHI) has become one of the most serious problems in many modern cities. Cities are considerably hotter since they have multiple heat sources, including vehicles, industrial production, mechanical equipment, and building materials with hard and reflective surfaces, which reradiate heat to the city environment, where it is then trapped in narrow urban canyons (Castleton et al., 2010; Parizotto and Lamberts, 2011). The UHI effect can be assuaged through the construction of urban parks, green roofs, and green walls to introduce more vegetation into cities. With Plants absorbing heat, air temperatures are reduced; humidity levels are increased; buildings and sites are sheltered from the direct sun and wind, which leads to a milder microclimate.

2. Reducing air pollution

Various studies have been conducted with focus on how green infrastructure can help to alleviate air pollution (Srbinovska et al., 2021). The Particulate Matter (PM) which most composed of organic matter, black carbon and nitrate is among the pollutants that have a greater negative impact on human health (Heal et al., 2012). GWs allows the larger green area to reduce more PM with the same projected area (e.g., horizontal occupied area) in city. In Leicester UK, results showed that PM 2.5 (a category of particulate pollutant that is 2.5 microns or smaller in size, usually exhaust gases from different heating sources (Srbinovska et al., 2021)) concentration can decline by as much as 9% as a result of the dispersive effect of trees (Jeanjean et al., 2016). It is estimated that trees, grass and other kinds of green fences can sequester CO_2 by 1.7% to 2.8% (Foster et al., 2011). Green areas (lawn with trees or not) help to reduce air pollution, particularly PM. In terms of PM 2.5 concentrations, transect across a lawn with trees shows fewer peaks than one across a lawn without trees (Tong et al., 2015). Besides, studies concerning urban streets concluded that green walls and living walls are helpful to decreasing of nitrogen dioxide and PM 10 (a category of particulate pollutant that is 10 microns or smaller in size, such as emitted from vehicles and burning wood (Srbinovska et al., 2021)) concentrations by 15% to 23% respectively (Radić et al., 2019). As for some specific plants used in green facades and living walls, they have a reducing effect of PM 2.5 concentrations as high as 45.3% and 74.1% respectively when tested in an enclosed space (Viecco et al., 2018).

3. Aesthetic Appeal

The most obvious benefit of green-wall systems is their aesthetic function. This has probably been the main driver for their adoption over recent years (Hedblom et al., 2019), and companies can improve their environmental brand or image by adopting a green wall. (e.g. the retailer Marks and Spencer in the UK has a number of green walls on its stores). GWs can be used as a landscape with multiple forms to embellish the city landscape. Although aesthetics can be a prime motivator, there are other benefits, the extent to which these can be realised by the choice of wall system (e.g. ones that require little energy), plant selection and management regimes. Depending on the style of architecture, green walls can improve the aesthetics of the building, 'softening' the hard dimensions of the urban landscape and promoting the concept of life within the city centre (Hedblom et al., 2019). Generally, GWs are more conspicuous than green roofs, as they are easily seen from the street level (Wood et al., 2014).

4. Psychological Impact on Urban Dwellers

Plants are known to have positive effects on the psychological and physiological health of individuals (Wood et al., 2014). For some situation, the GWs could not only improve the aesthetic appeal of the local environment but also benefit the urban dwellers from the perspective of psychological health. Green views, including facades, are thought to relax the mind and provide restoration from stress and anxiety. This could be especially important in inner city areas where there is little natural greenery, but where green walls can provide some respite from monotonous grey tones. Green walls may also reduce local heat effects (including inside the building) as well as have a positive effect on local air quality (Velarde et al., 2007; Feitosa and Wilkinson, 2018; Cameron et al., 2020; Srbinovska et al., 2021). Both these factors can influence human physical health. In addition, multiple studies demonstrated that a visual connection with exterior vegetation for people inside buildings could promote the generation of positive emotions (White and Gatersleben, 2011). Additionally, people with breathing diseases caused by urban pollution, such as asthma or allergies, could greatly benefit from the air filtering and oxygenating abilities of plants (Peck et al., 1999).

5. Providing Biodiversity and Creating Natural Animal Habitats

Urbanization changes the physical conditions of the soil, air and water, leading to the significant change of environment of the surrounding biological habitat. Extensive traffic networks fragment the urban habitat and harm the original natural ecological environment.

Although the green wall, as a special kind of biological habitat, couldn't ultimately solve the problems of urban habitats, it still plays a vitally positive role in the enrichment of the biodiversity in urban areas (Mayrand and Clergeau, 2018). A British study analysing the biodiversity of vertical urban surfaces found that building walls and façades could provide certain species of plants and animals with favourable conditions (Darlington, 1981). According to this study, the most common organisms found on exterior vertical walls are algae and lichens. These species can grow in minuscule crevices and holes. Other typical façade dwellers are mosses, ferns, liverworts, *Sedum*, herbaceous plants, vines, grasses, and even some coniferous plants (*Taxus baccata* - yew). These plant types are well adapted to vertical life because they can dwell in crevices and cracks, rely on building surfaces for support, and survive with small amounts of nutrients and water. Also, a thick layer of vegetation on building façades makes an appealing habitat for insects, birds, and small animals (Steiner, 1994; Francis and Lorimer, 2011; Chiquet et al., 2013).

6. Noise attenuation

In many urban areas, street noise could reach such a high level that it can disturb the concentration and ultimately lead to psychological stress for local inhabitants and pedestrians. The noise of traffic, sirens, horns and construction, a common element of urban life, bounces between the hard surfaces and is amplified and redirected during this process. Yet the thickly vegetated green walls can not only deaden the urban noises but also remind urban citizens of nature, visually and auditorily, in otherwise intense and hysteric environments (Wood et al., 2014).

7. Benefits for stormwater management

GWs are considered as the necessary element for urban drainage system to be sustainable because GWs can lessen surface runoff as well as decrease stormwater flows (Lau and Mah, 2018). Rainfall penetrates through modular GWs, as a result of which the runoff rate drops and urban stormwater management can benefit (Loh, 2008). GWs can be irrigated with stormwater gathered and this in turn will further make evapotranspiration on-site and infiltration rate higher.

8. Reducing light pollution

Most materials used on the surface of modern buildings could reflect both natural and artificial light. Despite the aesthetic function of the reflected light on the buildings' exterior, the excessively bright environment would cause visual fatigue, especially for drivers, which leads to traffic accidents at night. However, plants attached to the building surface could greatly weaken the intensity of the reflected light when light shines on the leaves and petals of the plants, and thus contribute to creating a safer environment for urban traffic (Wood et al., 2014).

1.5.2 The Benefits of Green Wall in Building Scale

1. Improvement of building energy efficiency and protecting the built façade

Façade plants have various positive effects on building thermal performance. Compared with the traditional walls (such as brick wall or stone wall), GWs can reduce temperature of the wall by reducing the thermal radiation and heat conduction by blocking the direct sunlight in summer. While in winter, GWs can increase the wall temperatures by decreasing energy loss with the “insulation layer” made by plants on the walls (Alexandri and Jones, 2008; Yoshimi and Altan, 2011). Research shows that shading with plants leads to lower temperature gradient of a building's exterior walls and because of the good heat conduction through the opaque building envelope. Though evapotranspiration cools and humidifies the air around the plant layer, the porous structure of the plant layer, formed by foliage and branches, lowers air movement near the façade (Ghaffarian et al., 2013; Zhang, 2013; Cameron et al., 2014; Paull et al., 2018).

Façade vegetation shelters wall construction below the plant layer from ultraviolet radiation which could cause material deterioration. By diminishing the daily temperature fluctuations, plants could reduce internal stresses in building materials, resulting in material cracking and premature aging. On extreme days, the temperature of an exposed façade can vary between -10°C and 60°C while that of a plant-covered façade fluctuates only between 5°C and 30°C (Wood et al., 2014).

2. Agricultural benefits

Green walls can be used for the growth of agricultural plants, such as tomatoes (*Solanum lycopersicum*), eggplants (*Solanum melongena*), zucchinis (*Cucurbita pepo*), squash (*Cucurbita. pepo*), cucumbers (*Cucumis sativus*), beans (*Phaseolus vulgaris*), and grapes (*Grapevines*). Therefore, in some circumstances with suitable climates, vertical surfaces in cities provide the potential space to build urban micro-farms, where neighbourhood residents have the chance to grow fresh product for their own use. Local product grown in urban farms is fresh, seasonal, and readily available when needed by city residents. Such farms could grow into a centre of local community life as well. Some manufacturers are recently developing commercial products on the wall that can be used to grow food vertically, for example, the Green Living wall system by Green Living Technologies LLC (Green Living Technologies) and the Reviwall system by Reviplant (Wood et al., 2014). An archetype of such an edible wall was set in Gladys Park, a poor neighbourhood in Los Angeles, by Green Living Technologies LLC (Giacomello and Valagussa, 2015).

3. Increasing property value

Several studies have shown that the property value can be increased by up to 20% by several vegetated features in buildings, such as green roofs or green walls (Miller, 2008; Pitts, 2008; Fuerst and McAllister, 2009; Eichholtz et al., 2010). Independent research conducted by the UK-based Royal Institute of Chartered Surveyors (RICS) on buildings in the USA, Canada and UK has concluded that at "the sustainable features of green buildings can add value to real estate". Buildings with substantial green elements have two main advantages: the first is that they can exert a positive influence on environment and human health; the second is that they can provide productive places to live and work, guarantee higher rents and prices, quickly attract tenants, decrease tenant turnover, and reduce the cost of operation and maintenance (Davis, 2005).

4. Sustainability rating system credits

Buildings with vertical greenery can often receive credits in Sustainability Programs such as the Leadership in Energy and Environmental Design (LEED) program, the voluntary green building rating system by the US Green Building Council (US Green Building Council, 2013) and BREEAM which using standards developed by BRE. Green walls could, independently or together with other sustainability building elements, be conductive to a building's LEED certification in every category including Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation in Operation (Wood et al., 2014). Green walls can also award the relevant credit by LE 04 calculator if it has been support with strong evidences in species richness (BREEAM, 2017).

1.6 THE ADVANTAGES AND DISADVANTAGES OF LWS

Compared with Green Facades, vegetation in the Living Wall Systems (LWS) is not just attached to a building surface, but fully assimilated into the whole construction where plants and growing media are both set on the vertical surface of the exterior wall (Wood et al., 2014). The function of the LWS varies with the different ancillary systems.

The main advantages of LWS over the Green Facades are:

1) Rapid arrangement. On one hand, LWS is open to a wider range of plant species. Green Facades are limited plant species choices that mainly the self-climbing plants (such as *Hedera*, commonly known as ivy), while LWS can provide favourable living environment for a wider range of plant species. In addition, the module of LWS is subject to rapid installation in the building and enables plants to cover the building surface in months, far quicker than the Green Facades that need years.

2) Flexible application. The advanced support systems in LWS (such as customized irrigation system, growing media, drainage system etc.) make LWS more applicable to all types of building surfaces and environments. Whereas the Green Facades is usually a typical outdoor greening technology, the LWS can be used both interior and exterior walls. As such, the LWS could be used as a vertical farming that produces food.

3) Recycle. The characteristics of self-climbing plant determine its low removability. As Green Facades can only accommodate self-climbing plant, the cost of removing plants to other environments from it will be high. By contrast, the relatively flexible LWS module allows a quicker and cheaper removal of plants from the LWS to other sites.

The main disadvantages of LWS are as listed:

1) High cost. The high costs of the initial capital investment (e.g., products, installing) and long-term maintenance LWS disassociate it with economic sustainability (Perini et al., 2013; Perini and Rosasco, 2013; Riley et al., 2019).

In terms of the initial capital investment, compared to Green Facades, LWS costs lots of money for each supports system which in the United Kingdom estimates currently range from 350 to 500£/m2 (Riley, 2017). For instance, the selected growing media is usually specific lightweight soil that has been processed manually; planting containers should be pre-made so as to have good corrosion resistance; the irrigation system and supporting frame even pose more special requirements on the materials selection and design, compared with traditional greening.

In terms of the long-term maintenance, the challenge for the customer's budget is that even a well-design system and appropriate selection of plants depend heavily on the successful maintenance. The challenges the traditional preconceptions of the building envelope's operating budget (Riley, 2017). For example, the annual LWS maintenance cost can be 8.5% (Perini and Rosasco, 2013) or even 15% (Mathew and Salot, 2014) of the installation cost. One study estimates that the annual maintenance fee is about a 1/3 of the cost of installing an LWS (Veisten et al., 2012). The use of these things adds economic pressure, along with a high initial capital investment and long-term maintenance fee. These together lead to the relatively high costs of LWS. Average installation cost (includes: initial investment, transportation, materials and labour) of 750 €/m^2 (641.24 £/m^2) and 18.98 €/m^2/year (16.23 £/m^2/year) was obtained for LWS based on research from Manso et al. (2021) and Riley (2017).

2) The limitation of plant selection. Although the LWS has larger range of plant species to select than the Green Facades, it is not suitable to plant tall and heavy species and is hard to fix plants with deep axial roots. Because LWS makes use of the planting module and frame as the bearer for the weight of the plant and the irrigation system, so for the system, the heavier the plant and base are, the more weight load it bears on the building. Therefore, the plant species choice is limited. Generally, shallow-rooted plants and low-growing shrubs are recommended. While the common climbing plants such as *Vitis* (grapes) and *Wisteria* cannot be used for LWS in this matter.

3) The lack of maintenance standard for LWS. Neither the LWS company nor the academic circle gives a clear LWS maintenance standard but only some suggestions. Therefore, the lack of research on standards for LWS maintenance could potentially lead to high consumption of natural resources and energy and high maintenance cost as well (Riley, 2017; Manso et al., 2021).

1.7 THE IMPORTANCE OF IRRIGATION FOR LWS

In recent years, the number of studies and publications on LWS has increased (Köhler, 2008; Suzuki, 2008). The hottest topics are: 1) Cost, such as the cost-benefit analysis (CBA) template which invent by Perini and Rosasco (2013) for the social benefits and costs of LWS, and generally overview the existing benefits and costs of different types of green roof and green wall based on building scale benefits, the city scale benefits and life cycle costs from Manso et al. (2021); 2) plant species, such as temperature, water consumption, air purification efficiency of different vegetation on LWS (Cameron et al., 2014; Pettit et al., 2017), and 3) thermal effect, such as the thermal impacts of LWS on buildings and how has those impacts incentive been used in the LWS design (Cuce, 2017; Olivieri et al., 2017; Lee and Jim, 2019).

However, the discussions above seem to evade a simple and objective fact, that is, the growth state and 'quality' of plants on GWs will not always be consistent. To the layperson the fact that many plants go dormant in winter and shed their leaves may come as a shock when desiring a mantle of green uniformly throughout the year. Potentially more serious is the fact that plants may lose quality through stress – drought / high temperature / root damage during cold weather and even overwatering; with ultimately in some cases plant failure (death). Green walls full of dead plants can be a public relations disaster for both the client and the green wall provider. Moreover all the desired benefits will be lost. In contrast to some of the points made above very little attention is paid to ensuring plants survive and perform well on green walls. Thus management and maintenance activities that ensure survival and performance need further research. The author believes that for all GWs research, especially the studies on LWS, the maintenance issue is among the rudimentary bases for any elaboration (Fig 1.5). The following researchers also share the author's view on the importance of maintenance:

> *"All green roof and green wall systems, from extensive to intensive, will require structural and horticultural maintenance…"*
>
> *Calkins (2012, p. 511)*

> *"Without question, the need for maintenance an important criterion in selecting landscape plants, and it appears to be growing in importance."*
>
> *Flint (1997, p. 8)*

> *"Technology can assist the development of methods for systematic and long-term maintenance of landscapes, which is one of the most effective means of slowing deterioration from human and natural agencies"*
>
> *Congress of the U.S Office of Technology Assessment (1987, p. 6)*

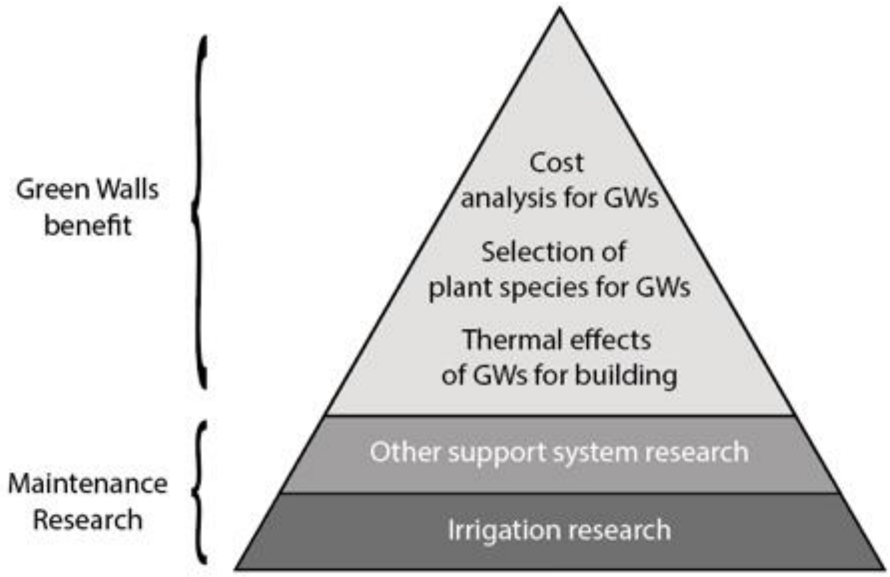

Figure 1.5 Illustration of the role of maintenance research on LWS

GWs maintenance can be divided into three aspects which are: 1) the structural issues, 2) the irrigation related issues, 3) and the horticultural issues (Arsenault, 2013). This research focuses the irrigation of LWS due to the following reasons:

1) Water is an important natural resource for all life. Optimizing the irrigation management of LWS is not only of great importance for urban water conservation because of the increasing water losses, but also help to improve the intra- and inter- city water distribution that are of great importance.

2) Compared with Green Facades, LWS has faster iteration and thus a greater market prospect. In addition, LWS has higher requirements for irrigation systems. In contrast, the plants of Green Facades are usually directly planted in natural soil, using natural water resources (such as rainwater), so they normally do not require additional irrigation systems.

3) As the most basic LWS maintenance method, irrigation can maintain the normal growth of the LWS to a considerable extent, so that the LWS can bring positive benefits (such as energy saving and emission reduction in buildings). These positive benefits can be quantified to offset the initial high cost with a clear calculation.

4) Traditional planting experience shows that the growth rate of plants is subject to the change of the irrigation strategy. Therefore, while ensuring the aesthetic quality, appropriately reducing the growth rate of plants will not only effectively extend the life cycle of LWS, but also significantly reduce the frequency and cost of subsequent maintenance (e.g. labour cost).

5) Research on irrigation of LWS can be used as a research template for other maintenance technologies.

1.8 THE MAIN PROBLEMS OF LWS IRRIGATION

The current irrigation problems of LWS mainly concern the following points:

1) To maintain the water status in the growing medium of LWS is highly dependent on irrigation system due to LWS's relatively low ability to obtain water directly from nature (i.e. rainwater). The limited size (for economic and safety reasons (Medl et al., 2018)) and vertical placement of LWS container decide that limited soil area is weak in absorbing rainwater and that rainwater drainage is faster in steep surfaces of LWS (Access Irrigation, 2015). As a result, the growing media and vegetation will not have adequate water available, if only supplied with rainwater from nature (Medl et al., 2018). Plants will face high moisture stress and even wilt in such adverse conditions as drought and high temperature in summer (Lisar et al., 2012; Signarbieux and Feller, 2012).

2) Research on the LWS irrigation design is limited. In consideration of the load-bearing ability of the building, LWS usually adopts a lightweight design. Consequently, the container that carries the growing media is usually not large in volume. This will lead to the overall low ability of LWS to maintain moisture (Pitha et al., 2011), which means that irrigation of high performance of is necessary for the LWS to keep its growing media moist continuously (Pérez-Urrestarazu et al., 2014). However, there are few studies discussing this issue. As mentioned by Hunter et al. (2014) and Medl et al. (2018), most of the current research mainly focus on how to supply adequate water without giving attention to the importance of irrigation intensity (Table 1.4). Most research on irrigation refer only to a simple irrigation method such as over irrigation once a day or two days, which causes a severe waste of natural resources and even plant death due to the root suffocation by imbalanced moisture content in the LWS (Segovia-Cardozo et al., 2019).

Table 1.4 Overview on irrigation management research (Medl et al., 2018)

NO.	SOURCE	LOCATION	VEGETATION	IRRIGATION SYSTEM	IRRIGATION FREQUENCY
(1)	Cheng et al. (2010)	Hong Kong	Grass	Irrigation pipeline	Twice a day
(2)	Chen et al. (2013)	China	Not defined	Sprinkler system	Once a day
(3)	Coma et al. (2017)	Spain	Evergreen	Drip line	Daily
(4)	Djedjig et al. (2017)	France	Not defined	Drip line	Twice daily (5 min)
(5)	Mazzali et al. (2013)	Italy	Evergreen and perennial	Drip line	Not defined
(6)	Olivieri et al. (2014)	Spain	Sedum	Drip line	Not defined
(7)	Ottelé et al. (2011)	Netherlands	Fern	Drip line	Not defined
(8)	Razzaghmanesh and Razzaghmanesh (2017)	Australia	Perennial	Drip line	Not defined
(9)	Scharf (2012)	Austria	Perennial	Drip line	According to demand
(10)	Serra et al. (2017)	Italy	Evergreen and perennial	Drip line	Every two hours (2 min)

3) The potential shortcomings of irrigation systems are (Irwin (2015): plant mortality caused by overwatering and subsequent an aerobism of the plant roots (Fig 1.6); inconsistent watering e.g. via a blocked dripper causing localised dry patches and plant death through drought. Irwin (2015) summarizes four problems in green wall irrigation management: 1) Overrunning timer; 2) Inflexible maintenance that fails to adjust the frequency seasonally; 3) Poorly-designed systems where the upper part of the wall is dry compared to the lower one; 4) Incorrectly-zoned wall. These problems can be solved by more frequent modification of the irrigation schedule by skilled technicians. However, due to time and cost limit, this is difficult to achieve. But there is a potential solution called "smart irrigation control system", a new type of irrigation system used in landscape maintenance.

Figure 1.6 Plant mortality caused by over-watering and subsequent an aerobism of the plant roots, back-side of the growing media (left photo) and front-side of the growing media (right photo) of lightweight plane LWS (Irwin, 2015)

1.9 POTENTIAL SMART CONTROLLER FOR LWS IRRIGATION SYSTEM

A high-performance irrigation system for LWS is determined by many factors, including solar irradiance intensity, LWS type, relative humidity, air temperature, growing media and vegetation characteristics (Pérez-Urrestarazu et al., 2014; Manso and Castro-Gomes, 2015). Some existing landscape irrigation technologies can be used as a reference to guide the research on LWS irrigation systems. Commercially, many irrigation systems are available, and they can be divided into four different types by the design, support facilities and working method: 1) sprinkler irrigation; 2) sub-irrigation; 3) surface irrigation; and 4) drip irrigation (Cetin and Bilgel, 2002). Commonly, LWS use drip irrigation systems to support plants growth. In these systems, water is transferred directly to the root of the plants by dripper. Runoff water and evaporation can be minimized if managed properly, compared with other three irrigation systems (Fan et al., 2015). In addition, there is a potential solution called "Smart Irrigation Controller" for landscape irrigation maintenance.

The use of smart irrigation controllers could be effective to realizing landscape irrigation where resources have their full play. A number of studies show that these controllers have good performance in conserving water in irrigation system (Beard and Kenna, 2008; McCready and Dukes, 2011). This is particularly true when it comes to well-maintained landscapes that have a high requirement for the right amount of water needed for turf grass and landscape plants.

Sensor-based smart irrigation controllers have some advantages over the traditional manually operated irrigation. For instance, in terms of irrigation strategy design, the use of the former is more beneficial for microclimate (e.g. including light, humidity and temperature) (Dukes, 2012). This new sensor-based controller provides an automated control method by analysing the environment data that is measured by sensors in real time. The basic key environment information includes: 1) soil; 2) plant; 3) local weather. These data are used to design a highly effective irrigation system, which helps to avoid the waste of water. Varieties of cases in past ten years show that the fast development of automated irrigation technology improve water conservation significantly (Haley and Dukes, 2007; Dukes, 2012). The most widely used sensor-based smart irrigation controllers are Weather-based (also called Evapotranspiration based) controllers and Soil Moisture Sensor (SMS)-based controllers.

1.9.1 Weather-Based Smart Controllers

Weather-based smart controllers are also known as Evapotranspiration or ET controllers. Plants' evaporation and transpiration process, if blended together, creates the short term, evapotranspiration, the latter part of which happens in the surfaces of soil and plants (Allen et al., 1998). The main aim of using an ET controller is to balance energy budget that exchanges energy for outgoing water at the surface of the soil and plant (Davis and Dukes, 2010). The net water loss from the crop field or landscape to the air is, in essence, equal to the loss during ET process (Semmens et al., 2016).There are generally three types of ET controllers: Signal Based ET controller; Historical ET controller; and On-site Weather Measurement (Fig 1.7).

1. Signal Based ET controller: Weather information is obtained either from public open resources or from agreement with weather station networks (Dukes, 2009). According to the weather information, the ET value will be calculated by controller for a hypothetical standard turf surface for that site (used as a reference figure). Then ET controller will be able to regulate the irrigation events.

2. Historical ET controller: The manufacturer or contractor needs firstly to programme the typical plant water usage data based on various environmental parameters into the controller. The irrigation timing and duration, however, may need to be adjusted accordingly to base on location-specific weather conditions such as the temperature or solar radiation, or indeed seasonal factors for any given site.

3. On-site Weather Measurement: This approach uses on-site weather information from local weather sensors to calculate ET value. Then this is used to calculate moisture applied via drippers to daily ET calculations.

Figure 1.7 Three brands of ET controllers (Dukes, 2009)

1.9.2 Soil Moisture Sensor (SMS) Based Smart Controllers

1.9.2.1 The definition of Soil Moisture Sensor (SMS) controller

Soil Moisture Sensor (SMS) controllers can be divided into two types: bypass SMS controller and on-demand SMS controller (Dukes, 2012).

The bypass SMS controller is the most commonly-used for small sites such as private gardens or urban residential yards. Typically, the core of the bypass SMS controller is a pre-programmed irrigation schedule defined by the user and only bypasses the watering event in some particular situations. For example, a bypass SMS controller has set safe soil moistures from “dry” to “wet”. In the pre-programed irrigation event time, the controller will check whether the current soil moisture content is within the safe range. If not and lower than the threshold, it will start the irrigation and supply water.

The on-demand type controller has two pre-programmed soil moisture thresholds of “dry” and “wet” respectively. The principle of this controller is that it keeps supervising the soil moisture, and it will turn the watering valve on or off when the soil moisture content feedback registers that the threshold has been reached. The main difference between these two soil moisture sensors is that the on-demand controller starts and ends irrigation events directly without any delay, while the bypass controller triggers irrigation events only when the timer requires (Dukes et al., 2009).

1.9.2.2 Workflow of SMS controller

The workflow of a SMS controller is as illustrated in Fig 1.8. The SMS controller receives the moisture content about the amount of water in the soil used and will turn on or off the switch accordingly. For example, once the soil moisture content decreases below the threshold value that is previously set by the user, the electricity and water valve will be connected to form a circuit loop. Then the controller will close the switch and initiate the irrigation (Haley, 2011).

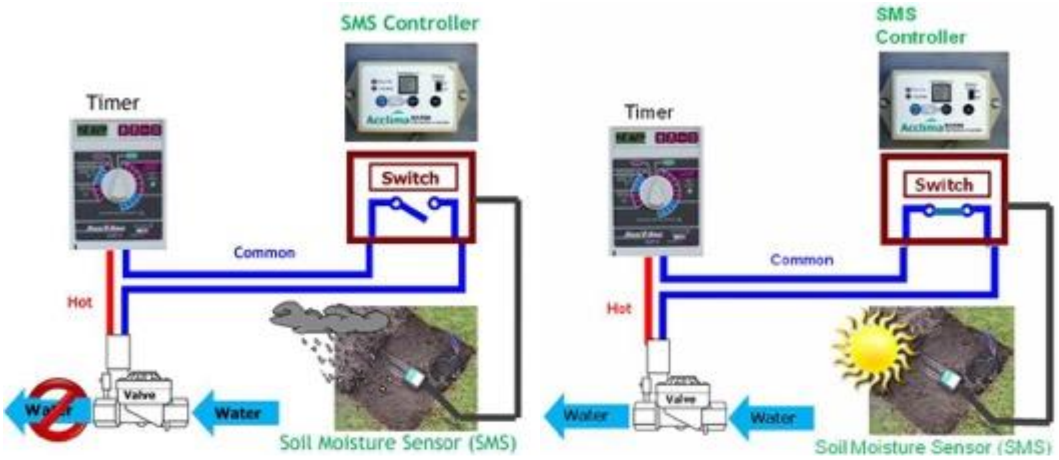

Figure 1.8 Simplified diagram of the soil moisture sensor (SMS) workflow (Haley, 2011)

1.9.2.3 Different types of SMS

SMS can be divided into two categories: "direct methods" and "indirect methods" (Table 1.5). The direct methods are easily understandable. The main idea is to measure soil water content directly by calculating the difference between moist soil and dry soil. Although the direct methods show high accuracy (± 0.0003, m^3) and low cost (Muñoz-Carpena, 2016), they have certain limitations; they are time-consuming, destructive and limited for making repetitions in the same location. Therefore, it would be a better choice to use indirect methods for the soil moisture measurement. In the indirect methods, measurements are conducted with calibration from some other measurable variables (Muñoz-Carpena, 2016).

Table 1.5 Different types of soil sensors

Soil water status field measurement	Direct methods	Thermo-gravimetric		
		Thermo-volumetric		
	Indirect methods	Tensiometric	Tensiometer	1. Tensiometer
			Electrical resistance blocks	2. Gypsum block
				3. Granular matrix sensors (GMS)
		Volumetric	Neutron moderation	4. Neutron Moderation
			Dielectric methods	5. Time domain reflectometry (TDR) 6. Time domain transmissometry (TDT) 7. Frequency domain reflectometry (FDR)

Soil water status is strongly related to two measurable variables: soil moisture content (SMC) and soil matric potential (SMP) (Schmugge et al., 1980). SMC is the amount of water contained in the growing media or substrate. It appears as a ratio ranging from 0 (where the growing media pores are filled with air alone) to saturation (where the growing media pores are full of water). While SMP represents the energy required to extract water from the growing media.

When soil is saturated, the SMP value is zero, and the value becomes negative when soil is dry. In natural environmental conditions, the range is from field capacity (FC) with the usual soil water pressures being -6 and -33 kPa, to soil permanent wilting point (PWP) representing the status of plant roots failing to suck water out from the growing media. The PWP that are commonly used to represent the SMP value in growing media is less than -1.5 MPa (Nolz et al., 2016). Theoretically, it is feasible to determine the upper and lower thresholds for irrigation by the plant's available water (PAW). In this case, the upper threshold value is the SMC at FC statement and the lower one is the SMC at PWP statement (Allen et al., 1998).

1.10 THE DEVELOPMENT OF SMART IRRIGAITON CONTROL SYSTEM COULD SOLVE THE PROBLEM OF THE DEVELOP OF LWS

In LWS, there is a variety of supporting systems to help plants to grow better, but not all LWS are equipped with every supporting system due to budget limit. Despite this, one system is basic and essential to LWS, namely the irrigation system. Medl et al. (2018) pointed it out that irrigation system is the core system in LWS as it could be quite beneficial. Good irrigation system could potentially reduce the maintenance cost for LWS by decreasing the human maintenance frequency as plant growth slows down. This beneficial idea comes from the sustainable "Landscape Naturalism Design". Although the concept is not fully applied in irrigation system, one of its important principles, reducing maintenance frequency, could be inspired in advancing irrigation system of LWS. To conclude, irrigation system is of great significance to LWS. Thus, the research on the advanced and smart irrigation system could be quite helpful to solving some current problems faced by LWS.

CHAPTER 2: MATERIALS AND METHODS

2.1 INTRODUCTION

A number of experiments of LWS performance were conducted between 2016 and 2019. The materials and generic methods are discussed here, with more specific experimental layout described in subsequent chapters.

2.2 EXPERIMENTAL LOCATIONS

The criteria for experimental site consist of two main parts: 1) Experiment requirement. Climate is the primary factor to explore whether different climate will affect plant growth on LWS. 2) Pragmaticism. A familiar site could potentially improve the accuracy of explanation of experiment results by researcher (Tellis, 1997; Yin, 2009).

Experiments were conducted in both Sheffield, UK and Jingmen, China. Sheffield experiments were located outdoors at the Goodwin Sports Centre of the University of Sheffield (coordinates 53°22'N; 1°29'W (Fig 2.1). The climate in the Sheffield is temperate maritime with mean annual rainfall of 834.6 mm, with December the wettest month (78.7 mm) and May the driest (53.8 mm). The average daily mean temperature in Sheffield ranges from 4.4°C (Jannay and February) to 16.9°C (July) between 1981-2010 (Met Office, 2021).

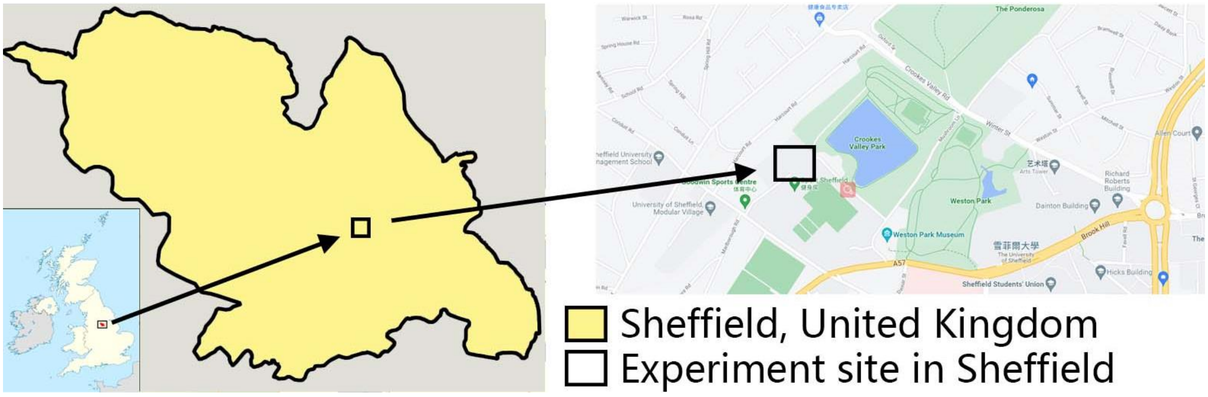

Figure 2.1 The location of the research experiment in the Sheffield, the United Kingdom (image: Google Maps)

In China, experiments were located in the residence area of Jingchu University of Technology, Jingmen City, Hubei Province, China (31°02'N and 112°12'E) (Fig 2.2). Jingmen is typical of humid subtropical climate. In Jingmen, the coldest month is January and the hottest month July. In July the temperature can reach as high as 38 °C at noon, but also falls below 0 °C in winter of regular annual snow. April to September has the highest rainfall, with rainfall decreasing in autumn and winter (China Meteorological Administration, 2021).

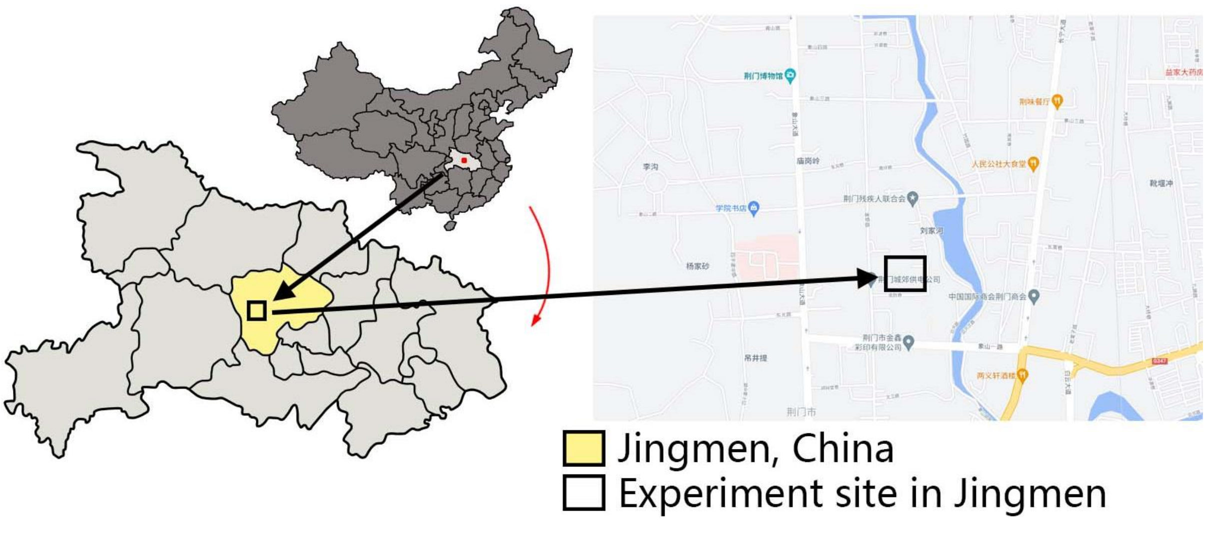

Figure 2.2 The location of the research experiment in the Jingmen, China (image: Google Maps)

2.3 THE COMPONENTS OF THE LIVING WALL SYSTEM

2.3.1 The Details of LWS Products

The products used in the LWS are all designed and developed by TreeBox Limited Company, Bosham, West Sussex, UK. A smaller module size (500 mm L x 1000 mm H x 150 mm W (Fig 2.3) was used in China, due to the logistics of transporting the larger, standard module used in the UK experiments (1000 mm L x 1000 mm H x 150 mm W). To compensate for this the Sheffield units were divided into two parts with a waterproof divider in the middle, making them comparable to the ones used in China. Thus there were 12 individual sub-units in total at each site and each of these had 5 layers (heights) (Fig 2.3).

Figure 2.3 The LWS systems used in the Sheffield (Top) and Jingmen (Bottom)

Each LWS units consist of 5 layers (bottom layer as the 1st layer and the uppermost layer as the 5th layer). Each layer contains 3 individual plants (recommended by TreeBox) which were positioned equidistantly on the left, middle and right sides respectively (Fig 2.4). Therefore, each LWS unit include a total of 15 individual plants.

Figure 2.4 The position of three individual plant species in LWS containers

2.3.2 The Details of LWS in The Experiment 1 and 2

In Sheffield the experiment was conducted in open space of Goodwin Sport Centre, The University of Sheffield, Sheffield. The LWS was attached to a wooden fence (7200 mm length x 1500 mm height x 30 mm width, Fig 2.5) and was oriented due to the slope of the site to face east. Many long strips of wooden fence rails (100 mm x 100 mm x 1500 mm) were used as re-enforcement strapping in the shape of "X" so as to strongly support the LWS modules and to resist the possible deformation and overturning caused by natural factors (wind and rain).

Because the site is on a slope, the gradient was used to rectify the angle in building the temporary wooden wall, thus ensuring that the wall is absolutely horizontal and vertical (Fig 2.6). All wooden materials were purchased from Hillsborough Fencing Company Ltd. Sheffield, UK.

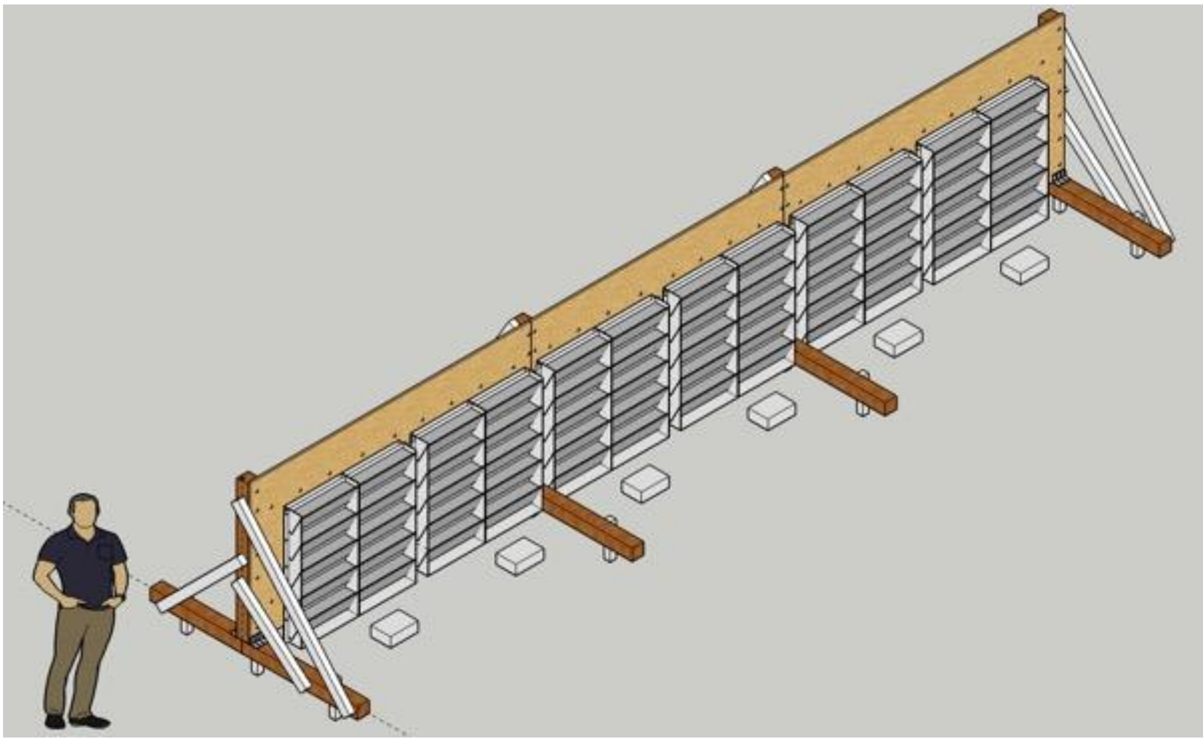

Figure 2.4 The wooden wall which designed by author for supporting LWS

Figure 2.5 The LWS used in Experiment 1 and 2 at Sheffield, the United Kingdom

In Jingmen, the LWS was placed on the roof of a three-story building (Staff Living Building of Jingchu University of Technology, Jingmen) and east facing (E). No high-rise buildings or trees were near this building, thus this LWS was also in an open sunlit location. The LWS was attached to a cement wall and due to the rooftop location (high wind and rain) a stainless-steel frame (6000 mm length x 1500 height x 30 mm width) built around both the cement wall and LWS to ensure no structural damage during adverse weather. As the roof also had a gradient the frame was constructed to avoid this to ensure the wall is absolutely horizontal and vertical (Fig 2.7).

Figure 2.6 The LWS used in Experiment 1 and 2 at Jingmen, China

2.3.3 Pot based experiment (Exp 3)

The pot experiment (Exp. 3) was only conducted in Sheffield. This was used to determine the effect of shading on plant growth of the species being used in the other experiments (Exps 1 and 2). The 2-Litre plant pot (JustMust Perennials, Evesham, UK) was used as the standard planting container unit in Exp. 3 as this pot can accommodate a similar volume of growing media as used by plants in the LWS system, and furthermore the pots allowed flexibility to lift and re-arrange plants as necessary. Plants of each species were arranged in two blocks (rows) within an 'open' environment that maximised natural sunlight (sun treatment). Conversely other rows of the same species were shaded using an overlay of "Blooma Polyvinyl Chloride (PVC) Mosquito Netting" (Fig 2.8). Each row of plants was represented by 8 specimens and with 2 species under study this equated to 96 plants (2 species x 2 treatments x 3 rows x 8 plants, JustMust Perennials, Evesham, UK). All pots were placed on wooden blocks (1200 mm L x 150 H x 1200 mm W) to stop plants rooting through to the underlying substrate and to mimic the conditions found in the LWS.

Figure 2.7 The LWS used in Experiment 3 at Sheffield, the United Kingdom

2.4 THE DETAILS OF IRRIGATION CONTROL SYSTEMS

2.4.1 Irrigation Treatment Design

The soil moisture content indicates the amount of water present in the soil (Denmead and Shaw, 1962; Verstraeten et al., 2008; SU et al., 2014). It is measured directly by the SM150T Soil Moisture Sensor (moisture accuracy of ± 3% with the built-in temperature sensor achieves ± 0.5°C, Delta-T Devices Ltd, London, UK) in this research. Based on suggestions from SM150T user manual (Delta-T, 2017), the soil moisture content can be easily calculated:

1) Convert Volts V to $\sqrt{\varepsilon}$ using the following equation.

$$\sqrt{\varepsilon} = 1 + 14.4396\,V - 31.2587V^2 + 49.0575V^3 - 36.5575V^4 + 10.7117V^5$$

Where V is the SM150T soil moisture sensor output converted from milli-Volts to Volts, the $\sqrt{\varepsilon}$ is the refractive index of water in soil.

2) Convert the $\sqrt{\varepsilon}$ value to soil moisture content θ.

$$\theta = (\sqrt{\varepsilon} - 1.16)/7.41$$

Where θ is the soil moisture content, the $\sqrt{\varepsilon}$ is the refractive index of water in soil.

Finally, the irrigation treatments were designed to provide three different soil moisture conditions: Dry Irrigation Treatment (from 15% to 40% soil moisture content); Medium Irrigation Treatment (from 40% to 65% soil moisture content) and Wet Irrigation Treatment (from 65% to 90% soil moisture content). The lower limit of the dry irrigation is set to 15% because anything less than these risks localised severe drying and the plant reaching permanent wilting point, and subsequent death. The upper limit within the wet irrigation was set to 90%, rather than 100% due to the characteristics of drippers irrigation which shown in Fig 2.9. There is an insufficient watering zone by dripper irrigation method when the plant root zone is fully watered. However, when the soil moisture content of entire growing media reaches 100%, it will significantly increase the possibility of water overflow on both sides of the container and lead to serious water waste. Dripper irrigation causes the water flow in the substrate to appear cone-shaped. Compared to manual irrigation, this kind of dripper technology will quickly wet the soil centre around the dripper. Especially, because the dripper itself will be inserted into the soil, hysteresis is predicted for the moisture to spread to the upper layer and the soil not adjacent to the dripper, because of the free movement of water molecules. Since the SM150T SMS monitors the moisture content of the entire container, attempting to achieve 100% moisture content (i.e. cover every potential dry spot) will lead to serious over-irrigation and direct run-off from the LWS. This does not conform to good practice in LWS management.

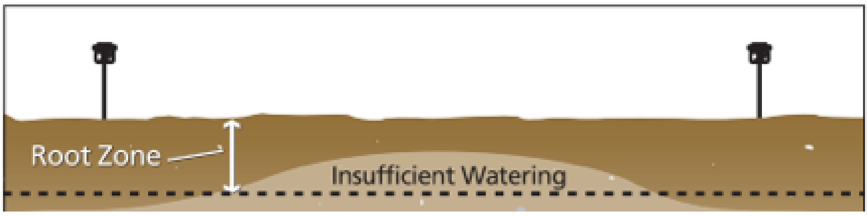

Figure 2.8 An example of insufficient watering in LWS container under dripper irrigation

2.4.2 The Prototype Model of Smart Irrigation Control System For LWS

For this research, a prototype model of smart irrigation control system for LWS is needed and it was invented by the author himself, which includes: 1) work flow design, 2) motherboard design, 3) code design and, 4) manufacture and assemble. Each part is detailed in the following subsections.

2.4.2.1 The overview of prototype model of smart irrigation control system

Fig 2.10 illustrates the overview of prototype model of smart irrigation control system for LWS. From left to right are three columns respectively: Input, Software and Output. Blue blocks represent software components while grey ones stand for hardware parts. The control system comprises four parts, which are: 1) Irrigation control unit, to analyse moisture data from sensor units and compare it to the irrigation treatments from database so as to execute the irrigation command. (This unit in the future could collect and process data to auto-schedule irrigation treatments intelligently); 2) Sensor units: to measure the moisture content of growing media. It used the SM150T SMS; 3) Server and database: to establish connections between user and control unit, store the data including the plant characteristics, climate information, and irrigation treatments etc. Communications are of two types: wireless communication (ZigBee) and wired communication (wires). 4) End-use software: allow users to directly control the irrigation, pre-set irrigation treatments, view current moisture content from each individual sensor unit, view and store irrigation history.

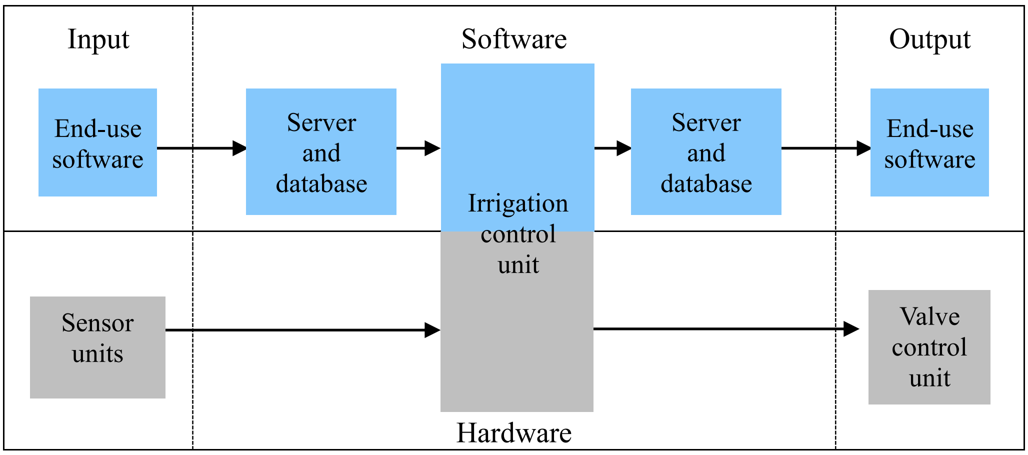

Figure 2.9. The overview of prototype model of smart irrigation control system for LWS

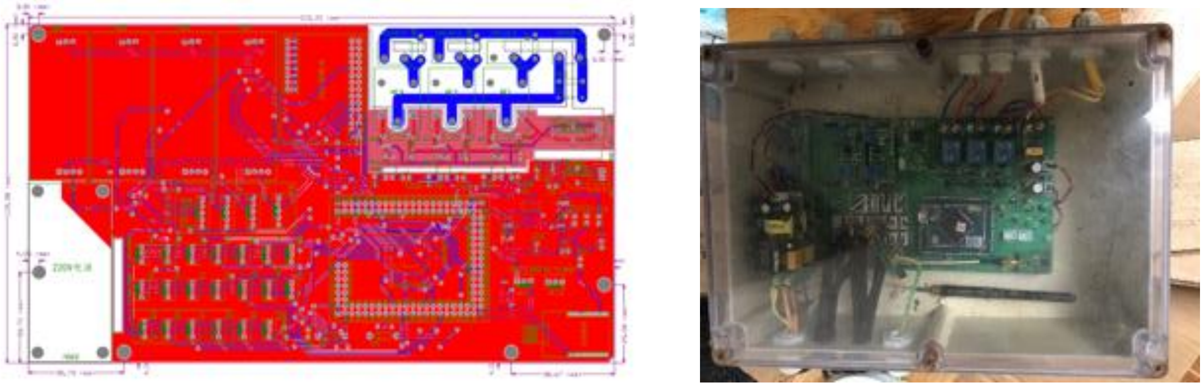

Figure 2.10. The motherboard design and assemble of prototype model of smart irrigation control system for LWS

2.4.2.2 Valve control unit

The Fig 2.12 shows the work flow of valve control system and the overview of the design. This unit includes 4 parts: 1) Water filter: to purify the water in order to prevent dripper from being blocked by impurities) (Fig 2.13c); 2) Water pressure converter: to ensure that the same amount of water passes through the pipes every second for both Chinese and British experiments) (Fig 2.13d); 3) Water valves: there are 12 individual water valves corresponding to 12 LWS units, one for each in every experiment site. This allows independent irrigation event for each LWS unit (Fig 2.13e); 4) Drippers: each plant is fitted with a dripper to ensure quality irrigation. The drippers applied in two different experiment sites are of the same specifications (2 L/H) (Fig 2.13f).

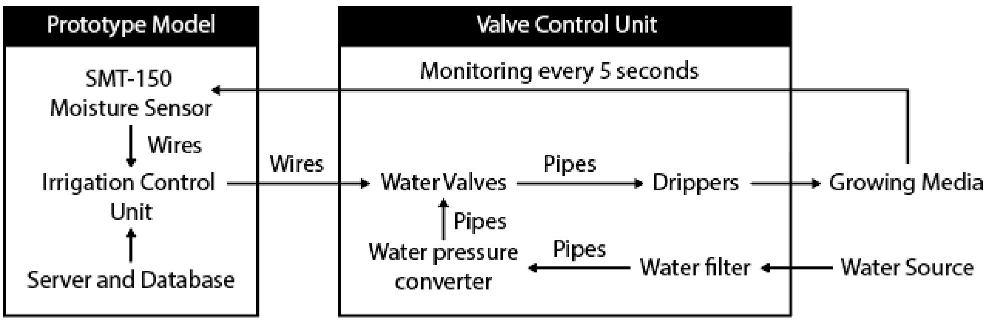

Figure 2.11 The work flow of the irrigation activity

a. overview of valve control unit

b. valve group

c. water filter

d. water pressure converter

e. water valve

f. dripper

Figure 2.12 The overview of the valve control unit

2.5 PLANT MATERIAL

In order to explore the influence of plant irrigation system on the growth of plants in LWS environment, four principles of plant selection were identified: 1) Significant differences in plant characteristics to illustrate how different species use water and adapt to extremes of availability. Plants were selected to provide a range of traits with respect to potential water use such as large leaves v small leaves, variation in colour. (Table 2.1). These characteristics could help explore more details about the effective on plant growth under different irrigation for LWS; 2) Adaptability to growth within the LWS. The growing environment of LWS is different from that of ground growth (e.g. limited growing media). The selected plant species have to adapt to the conditions specific to the LWS environment; 3) Able to grow in the climate of both Sheffield and Jingmen. This research span two different cities with remarkably different in climate and geographical characters at the same time, the selected plants have to be suitable for two different cities. 4) Available in local plant nursery. This research uses pre-grown mature plants directly purchased from a plant nursery. And thus these need to be available in the local market both in quality and quantity.

Four plant species were selected based on known capacity to gown in LWS systems and be representative of different eco-physiological backgrounds i.e. shade loving woodland plants such as *Hosta* or those that prefer a more open aspect such as *Heuchera* (Table 2.1).

Table 2.1 The four different plant species used in the experiments (images resource: RHS)

	**Synonyms:** *Vinca major* 'Variegata' **Common name:** Bigleaf Periwinkle **Foliage:** evergreen **Sunlight:** Full sun, partial shade, full Shade **Drought tolerance:** Relatively high		**Synonyms:** *Hosta* 'Blue Mouse Ears' **Common name:** Plantain Lily 'Blue Mouse Ears' **Foliage:** Deciduous **Sunlight:** Partial shade **Drought tolerance:** Relatively low
	**Synonyms:** *Heuchera* 'Marmalade' **Common name:** Alum Root 'Marmalade' **Foliage:** Semi-evergreen **Sunlight:** Full sun and partial shade **Drought tolerance:** Relatively medium		**Synonyms:** *Hedera helix* L. **Common name:** Common English ivy **Foliage:** Evergreen **Sunlight:** Full sun, partial shade, full shade **Drought tolerance:** Relatively high

Vinca major 'Variegata'

Vinca could be categorized into subshrubs or herbaceous perennials. This plant is evergreen, having in the leaf axils simple, paired leaves and solitary, 5-lobed, salver-shaped flowers. The 'Variegata' is a kind of evergreen sub-shrub. It can reach a maximum height of 45cm, lead to a clump of erect leafy flowering stems as well as the long prostrate rooting stems. Their ovate leaves are margined with cream. This plant's flowers are violet-blue and are 4-5cm wide. Their opening period is from spring to autumn (RHS, 2020d).

Hosta 'Blue Mouse Ears'

Hosta are clump-forming herbaceous perennials. Their leaves are simple, ovate or lance-shaped. *Hosta* are usually coloured or chromatic. In early summer, it has racemes of nodding, funnel or bell-shaped flowers. For 'Blue Mouse Ears', it is a small, mounded perennial. Its leaves seem rather dull with their usually smooth, neat and blue-green surface. Its bell-shaped flowers are often 2cm-long.And their colour is pale purple with darker stripes (RHS, 2020c).

***Heuchera* 'Marmalade'**

Heuchera are almost evergreen, clump-forming perennials. Its leaves are rounded, shallowly palmately lobed with racemes or panicles of small, tubular flowers, usually with colourful calyces. 'Marmalade' has mounds of lobed and slightly ruffled leaves. Its shades have various colours: pink, bronze and yellow-brown, and their undersides are sometimes bright pink. Its clump can extend up to 45cm. In summer above the leaves, brownish flowers are borne on deep pink stems to 25cm (RHS, 2020b).

***Hedera helix* L.**

Hedera are evergreen climbing shrubs. They cling by aerial roots. Their clustered flowers are small yellow-green and they usually grow into black berries. Foliage of sterile, climbing shoots is often more deeply lobed than that of the flowering shoots. *H. helix*, which is self-clinging, climbs vigorously. Its leaves, usually three- to five-lobed, glossy and evergreen, are often with veins being pale green. The colour of the leaves will turn reddish or bronzy in autumn. Mature plants have bushy, non-clinging branches. Their leaves are diamond-shaped. Their flowers in clusters of rounded heads in autumn are small, nectar-rich, greenish-yellow. And these will grow into black berries in winter (RHS, 2020a).

Transplantation

Plants were sourced from a local nursery at a similar developmental stage (1 year old, established liners approx. 10 cm tall, growing in 1-Litre pot). In order to carry out the experiment effectively, after the plants purchased from the nursery were delivered, plants were carefully pulled out from the original pot, and then the soil adhering to the roots should be removed as much as possible so as to lessen the nutrition and virus in the original soil. Plant of same species would be randomly placed in LWS unit to avoid locational bias. Before this, each plants were re-pruned and thus looked similar (15 cm height x 15 cm spread). According to the guidance of TreeBox, it was required that before transplanting plants, a layer of growing media with a thickness of 40 mm was laid at the bottom of each LWS unit to ensure that there would be enough space for plant root to develop.

2.6 PLANTS GROWING MEDIA

Coir coconut fibre was chosen as the growing media. According to a report on the lifecycle assessment of growing media (Domeño et al., 2011), coir has a lower rate of organic matter loss than wood fibre. This is probably because the coir having a higher lignin content, the factor that makes it resist microbial degradation. In addition coir is considered superior to Rockwool in terms of distributing water vertically in LWS, and thus promoting root growth (Jørgensen et al. (2014). Coir was used consistently throughout the research to minimise variation based on media physical and chemical properties. A single composition of coir that are available in both

China and the UK, was Coco Professional Plus (consists of 100% coco flakes, CANNA BV, London, UK) from CANNA® (CANNA, 2020).

2.7 PARAMETERS THAT WERE RECORDED

2.7.1 Plant Phenotypic Measurements

Plant material was rated based on growth parameters and quality criteria. The measurement of plant growth includes four elements: the size of plant, the number of plant stems, the number of plant leaves and the number of flowers (Table 2.2). All data of selected plant indexes were recorded in Table 2.3.

Table 2.2 The selected plant indexes to be measured

CATEGORY	TERMS		
The size of plant	Height (mm)	Spread (mm)	
The number of stems	Number of stems		
The number of leaves	Number of large leaves (leaf width or height ≥ 30 mm)	Number of medium leaves (leaf width or height ≥ 5 mm < 30 mm)	Number of small leaves (leaf width or height < 5 mm)
	Number of new leaves (difference of leaf number than last record)	Number of damaged leaves (over 10% of a leaf were damaged or lost)	Number of wilted leaves
The number of flowers	Number of open flowers	Number of flower buds	

Table 2.3 The recording form for the selected plant indexes

Date:__________ Location:__________

Wall No.	Plant No.	Plant H	Plant Sp	Total St	Total L	Large size leaf (≥ 30 mm)	Medium size leaf (30 mm > x > 5 mm)	Small size leaf (≤ 5 mm)	Damaged leaf No.	Open blooms	Flower bud	Wilt Plant leaf
1	1											
	2											
	3											
	4											
	5											
	6											
	7											
	8											
	9											
	10											

The size of plant

The size of plant was measured every 15 days and includes two parts, the plant height (mm) and the plant spread (mm). Because the experiment focuses on the performance of plant growing in the upper part of the soil, and the length of plant roots cannot be accurately measured in the shared LWS container with other plant species, the edge of the container would be used as the reference baseline to measure the plant size (Fig 2.14). So to collect the data of the height of the final plant, the author would measure the part straightening out the stems that is above the reference baseline. All data about plant height and spread were measured with a 1 mm graded tape measurement tools (B&Q, Eastleigh, Hampshire, United Kingdom) in Sheffield by author and the data in Jingmen, China were collected by research assistant using a 1-metre graded tape (1 mm accuracy, Deli Ltd, Ningbo, China).

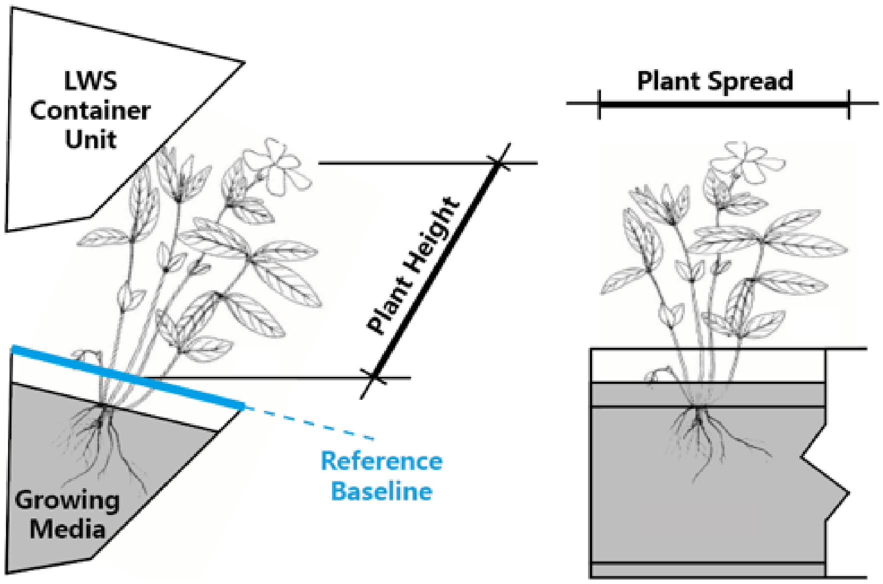

Figure 2.13 The measurement of the plant size

The number of plant stems

The total number of plant stems was counted every 15 days and should be considered valid only if the stem is taller than 1 mm. In this research, only *Vinca* was counted for the number of plant stems.

The number of leaves

Leaf counts were manually recorded by author in UK and research assistant in CN (Fig 2.15). These include the numbers of large-size leaves, medium-size leaves, small-size leaves, damaged leaves and wilted leaves. After that, the total number of leaves could be calculated by the sum of the numbers of different plant leaf sizes. In addition, the differences between plant leaves of different sizes are as follows. Leaf over 30 mm high or wide are defined as 'large'; with the leaf width or height less than 30 mm but greater than 5 mm as 'medium'; with the leaf width or height less than 5 mm as 'small'. Besides, the calculation of the number of new leaves is the result of the leaf number counted last time deducing latest leaf number.

Figure 2.14 The measurement of the number of plant leaves of different sizes (Photos taken by author)

The number of flowers

The number of flowers includes two separate kinds: the number of open blooms and the number of flower buds (Fig 2.16). The flower buds refer to the buds growing close to each other in the upper most parts of the stem.

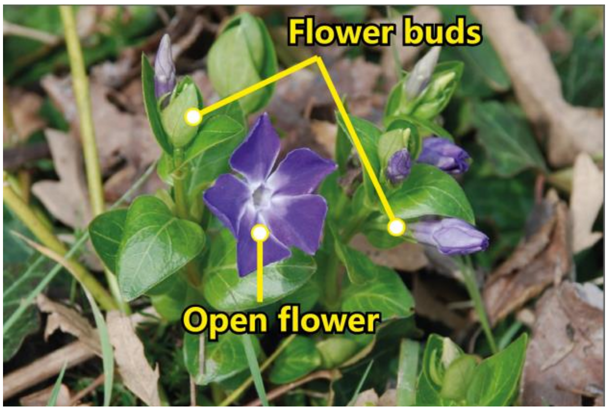

Figure 2.15 The plant open flowers and flower buds (Altervista, 2021)

2.7.2 Plant Aesthetics Rating Measurements

To avoid bias, plants were rated by the author for aesthetic criteria using photographs. He could not be present in the UK and China at the same time, so a research assistant took and sent photographs over from China. These were compared to images from the UK. Since the cameras from different manufacturers and production batches that have different performance in various aspects, like the noise and colour balance (Pointer et al., 2001; Richardson et al., 2009), which could potentially affect this photo-based assessment. Therefore, to diminish the difference potentially caused by the camera, the following cares were taken to ensure:

- The cameras and lens were the same model (Fig 2.17)
- Fix white balance was used instead of auto white balance as this can dampen the noise (Fig 2.18) (Richardson et al., 2009)

- A white paper in the field can be placed in the field as a reference to correct the colour balance of the photo (Fig 2.18)

The location of the camera (Canon EOS 60D) in these experiments is set as shown in Fig 2.17. In addition, Fig 2.18 shows comparison between photos before and after using the white colour paper as a reference to correct the white balance of the image by Camera Raw in Adobe Photoshop 2020.

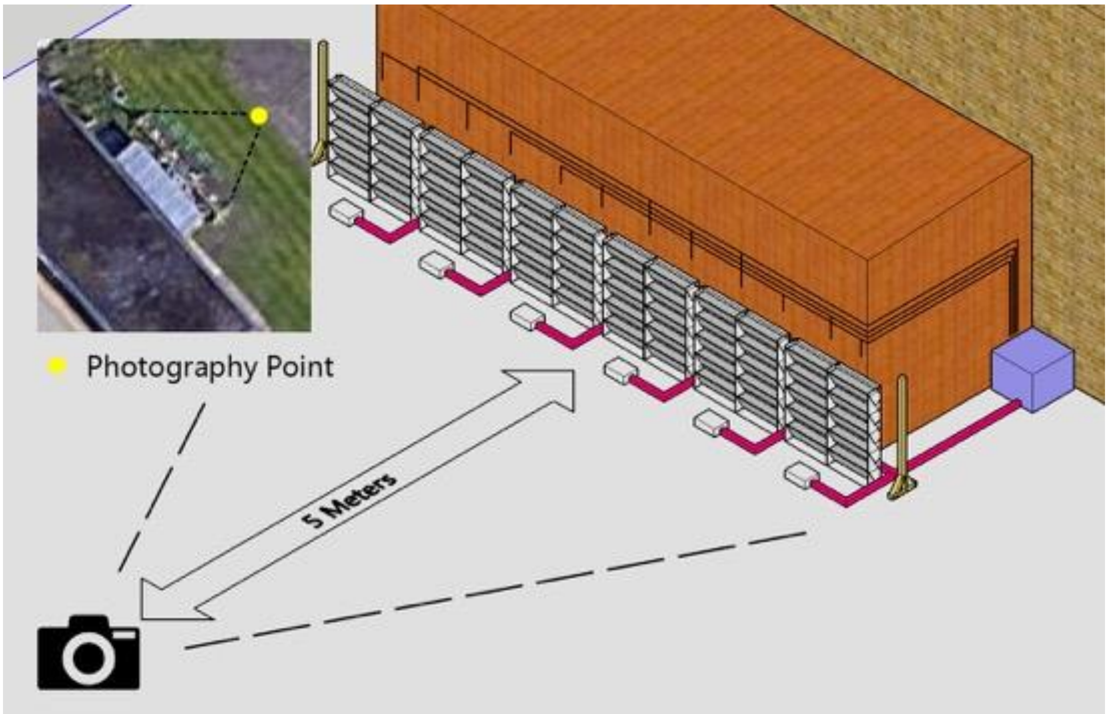

Figure 2.16 The location of photography (Satellite image from Google Earth)

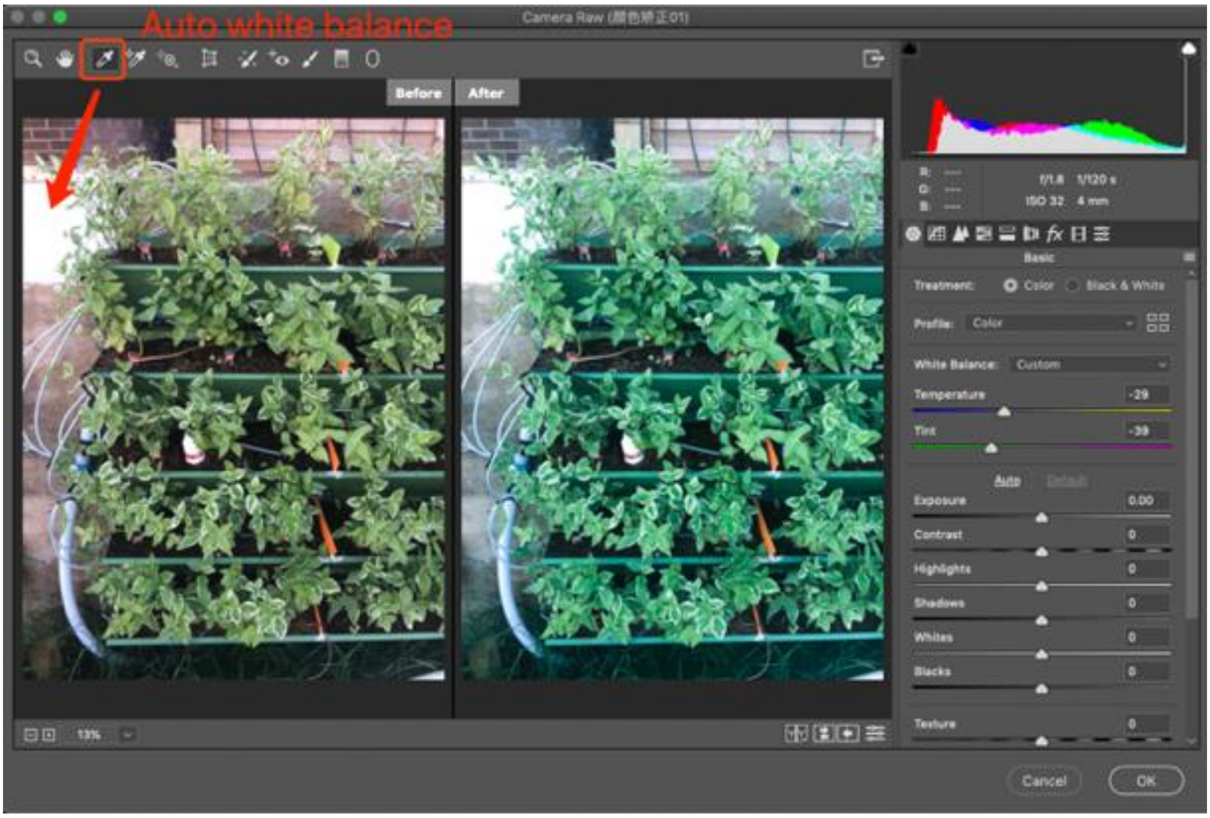

Figure 2.17 The correction of white balance of the image at Adobe Photoshop 2020

After collecting all plants' panorama photos, the author used the corrected white balance photos as the photos which provides the aesthetic rating with the help of the "aesthetic rating form (Table 2.5)". In order to avoid some human error, the final aesthetic rating of plants was determined by the average value after repeatedly evaluating plants' aesthetic performance for three times in different days. The vegetations visual quality was assessed by those photos from each 15 days. Use the rating scale proposed by Wilson et al. (2020) which is that 1 = dead or very poor quality, 2 = poor quality, 3 = good quality, 4 = very good quality, and 5 = excellent quality (Table 2.4).

Table 2.4 The definition of the plant aesthetic rating scale from 1 to 5

RATING SCALE	QUALITY	DEFINITION
1	Dead or very poor quality	Severe necrosis, chlorosis and/or bad form
2	Poor	Poor colour and form, large chlorosis and necrosis
3	Good	Good colour and form, some acceptable chlorosis and necrosis
4	Very Good	Very good colour and form, minimum chlorosis or necrosis
5	Excellent	Best colour and form, highly marketable plant material

Table 2.5 The aesthetic rating form for plants

Aesthetic Rating Form Date:___ Location:___									
Layer	Wall 01			Wall 02			Wall 03		
L1	4	4.5	4	3.5	4	4.5	3.5	3.5	4
L2	3	3	4	3.5	4	4	4	3.5	4
L3	3.5	3.5	4	3.5	4	4	3.5	4	3.5
L4	3.5	3.5	4	3.5	4	4	4	4	4
L5	4	4	4.5	3.5	4	4	3.5	4	4.5

* 1 = Dead or very poor; 2 = Poor; 3 = Good; 4 = Very good; 5 = Excellent

2.7.3 Environment Measurement

The environment data includes two parts, which are meteorological information and the information of growing media moisture content.

Meteorological information

The meteorological information was used to explore whether different environments could affect the plant growth performance under the same irrigation treatment at the same period of time. The data source of meteorological information is the local meteorological bureau, specifically the “The United Kingdom Met Office” and the “The Jingmen Meteorological Service”. Primary data was based on hourly averages and Excel was used to summarise this data. The data includes: the average daily air temperature (^{o}C) at 2 m above ground level, the average daily relative humidity (r.h.) at 2 m, the average daily precipitation (mm) and the average daily pressure (MPa). The sunlight intensity throughout the third experiment was collected with the SunScan Probe Type SS1 (0.3 μmol.m^{-2}. s^{-1} resolution with the accuracy of ± 10%, Delta-T Devices Ltd, London, UK). Unit is PPFD (μmol. m^{-2}. s^{-1}) and (1 PPDF = 54 Lux).

Both in Sheffield and Jingmen, standard meteorological data used for analysis came from weather stations near the experiment field. Detailed information on local meteorological bureau can be found in Chapter 2.3.4. Data were extracted every 1 minute and were store every 10 minutes.

Moisture content of Growing media

The moisture content of growing media was monitored by the SM150T SMS (moisture accuracy of ± 3%, Delta-T Devices Ltd, London, UK) and ML3 ThetaKit Soil Moisture Portable Kits (moisture accuracy of ± 1%, Delta-T Devices Ltd, London, UK). According to the recommendation from Delta-T, the probes of SM150T SMS are required to be completely embedded into the growing media, better in the centre of growing media (Fig 2.20). In order to get more accurate measurement, all sensors had been calibrated under the guidance from Delta-T before they were used (Delta-T, 2017).

Figure 2.18 The growing media used in this research (CANNA, 2020)

Figure 2.19 The location of the SM150T SMS in the LWS at left section view (left image) and perspective view (right photo)

As planning irrigation in this research requires real-time data, and it is impossible for the author to measure the moisture content every second, especially for experiments in two countries. Therefore, a prototype model of irrigation control system was developed to meet the requirements of the research. Due to the limited budget and the number of experiment equipment (these experiments require at least 24 sensors and each sensor sells £150), it is of great significance to conduct a pilot study to find out the appropriate number of sensors that should be used and location where sensors should be placed before the formal experiment.

There are three groups of experiments (Table 2.6) to determine the location of the optimal sensor in the pilot study, namely Reference Group, Group A and Group B. And all plants were numbered from 1 to 15. In the reference group, the overall moisture content of LWS unit was determined by the overall mean value of all 15 plants, the individual value of which was manually measured with ML3 ThetaKit Soil Moisture Portable Kits. In Group A, the overall moisture content of LWS unit was represented by the mean value of plant rep 2, 8 and 14, the individual value of which was measured automatically by three SM150T SMS set for the plant 2, 8 and 14 respectively. In Group B, the overall moisture content of LWS was decided only by the content value of plant rep 8, automatically measured by SM150T SMS. Before the pilot experiment, all plants were planted in LWS. After 7 days, when survival of all plants was secured, an over-irrigation was conducted so that the growing media absorbed the maximum amount of water possible. After 24 hours, the experiment started. In the following 15 days, the moisture contents were measured once a day at 12.00 pm. Finally, the accurate difference between soil moisture of the three groups could be identified by comparing data collected.

Table 2.6 The pilot study on sensors' location

	Reference Group			Pilot Study Group A			Pilot Study Group B		
	Measuring by portable sensor set in every plant			Measuring by three sensors			Measuring by one sensor		
Layer 1	**1**	**2**	**3**	1	**2**	3	1	2	3
Layer 2	**4**	**5**	**6**	4	5	6	4	5	6
Layer 3	**7**	**8**	**9**	7	**8**	9	7	**8**	9
Layer 4	**10**	**11**	**12**	10	11	12	10	11	12
Layer 5	**13**	**14**	**15**	13	**14**	15	13	14	15

The pilot study showed that for small size LWS unit of 1 m x 0.5 m, the moisture content measured in plant 8 alone could represent the average mean value of the growing media as the accuracy difference between the three groups was slight but not significant, falling within an acceptable range. But it should be noted that different LWS unit differs in its structure, so every LWS unit should have its own pilot study to find out the feasible alternative. In this research, a total of 24 SMS sensors were used, 12 for Sheffield and 12 for Jingmen. The arrangement of the sensors is as shown in Table 2.7. The measurement frequency and data storage frequency were 5 seconds and 1 minute, respectively.

Table 2.7 The location of plant and soil moisture sensor in LWS

	Wall 01			Wall 02			Wall 03			Wall 04			Wall 05			Wall 06			Wall 07			Wall 08			Wall 09			Wall 10			Wall 11			Wall 12		
L1	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
L2	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
L3	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9	7	8	9
L4	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12
L5	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15	13	14	15

*Red colour means the location of the Soil Moisture Sensor.

2.8 DATA HANDLING AND STATISTICAL APPROACHES

There are total of 5 different independent variables identified in this research which are irrigation treatments, plant species, location, time and shading degree. Those independent variables are selected and analysed with plant growth to achieve the relative research aims in each different experiment. All statistical analyses are performed with the Microsoft® Excel and IBM® SPSS® Statistics 25 in this research.

Data about plant physical size were using the "relative value" rather than "absolute value" in order to better understand the changes of plant growth. Those data were transformed by using the 'LG10 (max+1-x)' function, which retains the "negative number" (i.e. plant dieback) in the transformed data, in order to ensure the normal distribution. The multiple comparisons of means were obtained using the Bonferroni test due to the number of comparisons is small (only 5 times) and the potential unequal sample sizes (e.g. plant dead) leads the error on using Tukey HSD. More details of statistical analysis are presented in the following chapters.

2.9 EXPERIMENTS OUTLINE AND TIMINGS

The Experiment 1 aimed to compare growth rates in different species and determine the effects of irrigation treatment, location (countries) and time (with respect to natural growth phases) on shoot development, leaf number and aesthetic appeal. The aim of Experiment 2 was to determine how plants of different species grew, when they were grown together in a community scenario. In effect how would individual plants grow when competing for water, light and nutrients with specimens of another species when grow in the same LWS unit. Experiment 3 aimed to explore how different plant species will perform with different shading treatments (full sun and full shady) and irrigation treatments (the dry and the wet treatment) at the LWS environment. The summary of those three experiments as below (Table 2.8).

Table 2.8 The summary details of each experiment

EXPERIMENT	1	2	3
LWS type	Standard LWS	Standard LWS	2-litre pot
Date	Phase 1 (1 May 2018 to 30 Jun 2018) Phase 2 (1 Jul 2018 to 30 Aug 2018) Phase 3 (1 Sep 2018 to 30 Oct 2018)	Phase 1 (1 May 2019 to 30 Jun 2019) Phase 2 (1 Jul 2019 to 30 Aug 2019)	1 Sep 2019 to 30 Oct 2019
Air temperature range	2.4 to 23.4°C in Sheffield 12.8 to 32.0°C in Jingmen	6.4 to 26.1°C in Sheffield 14.8 to 31.9°C in Jingmen	5 to 12.5°C in Sheffield
Humidity Range	66% to 100% in Sheffield 24% to 99% in Jingmen	75% to 100% in Sheffield 45% to 97% in Jingmen	82% to 100% in Sheffield
Pressure Range	998.0 to 1033.2 in Sheffield 974.4 to 1001.7 in Jingmen	995.6 to 1035.2 in Sheffield 976.2 to 994.9 in Jingmen	992.2 to 1031.5 in Sheffield
Irrigation treatment	Dry (15% to 40%) Medium (40% to 65%) Wet (65% to 90%)	Dry (15% to 40%) Medium (40% to 65%) Wet (65% to 90%)	Dry (15% to 40%) Wet (65% to 90%)
Species	*Vinca major* 'Variegata' *Hosta* 'Blue Mouse Ears' *Heuchera* 'Marmalade' *Hedera helix* L.	*Vinca major* 'Variegata' *Hosta* 'Blue Mouse Ears' *Heuchera* 'Marmalade'	*Vinca major* 'Variegata' *Heuchera* 'Marmalade'
Key measured parameters	Plant size (plant height, plant spread, plant leaf number) Plant aesthetic rating Air temperature – daily mean Relative humidity – daily mean Precipitation – daily mean Pressure – daily mean	Plant size (plant height, plant spread, plant leaf number) Plant aesthetic rating Air temperature – daily mean Relative humidity – daily mean Precipitation – daily mean Pressure – daily mean	Plant size (plant height, plant spread, plant leaf number) Plant aesthetic rating The Photosynthetically Active Radiation (PAR) – hour mean

CHAPTER 3: EXP 1. THE EFFECT OF SINGLE PLANT SPECIES CHOICE, IRRIGATION, LOCATION AND TIME OF GROWTH

The objective of this experiment was to evaluate how irrigation supply affected plant development, when only a single taxon was in the growing module (i.e., no competition between species for the water or light available). Irrigation is important in keeping the plants alive, but can also optimise growth or even be detrimental to plants if the media becomes waterlogged. Irrigation levels can also be used to control growth (Feng et al., 2003; Seidel et al., 2017; Ierna and Mauromicale, 2018), thus perhaps reducing subsequent requirements for pruning (Cameron et al., 1999; Cameron et al., 2006). One aim of this experiment was to determine how level of irrigation (volume of water applied at any time) influenced growth rates and plant quality. This would be affected by climate and growth period, thus the experiment was implemented both in the UK and CN, and repeated at different times of the growing season. The location a plant grows in naturally (biome and range) and its ability to adapt to the environment (its ecophysiology) may affect its requirement for water and its impact on growth. As such landscape plant taxa were chosen that reflected differences in where their parent species came from, for example woodland species that tolerate either damp soil (e.g., *Hosta*) or dry soil (e.g., *Vinca*).

The following hypotheses were tested:

- The growth and development of plant will be affected by the water availability (Dry, Medium, or Wet) and its position on the wall.
- The effects of irrigation treatments will vary, depending on local climate conditions (Sheffield, UK vs Jingmen, CN).
- Species with large leaves and high shade-adaptation (e.g., *Hosta*) will perform less well compared to those that can adapt to drier conditions (e.g., *Vinca*).

3.1 MATERIALS AND METHODS

3.1.1 Experimental Design

For the Experiment 1, four plant species were selected namely; *Hosta, Vinca, Heuchera* and *Hedera* (see Chapter 2). Each plant species was represented by 45 individual plants and a total of 180 plants were used in the research for each experiment site.

This experiment was repeated 3 times in each geographical location during 1 May 2018 to 30 Oct 2018 (Table 3.1). This also allowed the research to take account of different temperature and rainfall patterns at different seasons. These three repeated experiments were defined as Phase 1 (Spring), Phase 2 (Summer) and Phase 3 (Autumn) (Table 3.1). The Phase 1 started from 1st May 2018 to 30th June 2018. It covered a range of average daily temperatures from 10.1°C to 18.4°C in the Sheffield and 17.8°C to 38.9°C in Jingmen. This period is also naturally low-growth season for selected ornamental plants; The Phase 2 started from 1st July 2018 to 30th August 2018. The range of average daily temperatures was from 12.9°C to 24.9°C in the Sheffield and 24.2°C to 38.2°C in Jingmen. Temperature at this time is relatively high, compared with that in other periods of a year. Long periods of daylight will pose much pressure on plant growth; The Phase 3 started from 1st September 2018 to 30th October 2018. It had a range of average daily temperatures from 3.1°C to 19.8°C in the Sheffield and 12.9°C to 32.6°C in Jingmen. This period is the cold temperature after summer. At this point, sunshine hours began to decrease.

Table 3.1 The schedule of the time arrangement, plant location in the LWS and irrigation treatments in Experiment 1

PHASES	TIME	PLANT LOCATION AND IRRIGATION TREATMENT											
		Wall 01	Wall 02	Wall 03	Wall 04	Wall 05	Wall 06	Wall 07	Wall 08	Wall 09	Wall 10	Wall 11	Wall 12
Phase 1 (spring)	1st May 2018 To 30th June 2018	Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
Phase 2 (summer)	1st July 2018	Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera

	To 30th August 2018	Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
Phase 3 (autumn)	1st September 2018 To 31st October 2018	Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera
		Vinca	Vinca	Vinca	Hosta	Hosta	Hosta	Heuchera	Heuchera	Heuchera	Hedera	Hedera	Hedera

*Red colour for dry treatment, yellow colour for medium treatment, green colour for wet treatment

Plants were pruned and moved by the guidance from Chapter 2.5. Three irrigation treatments were included, namely Dry Irrigation Treatment, Medium Irrigation Treatment and Wet Irrigation Treatment, respectively (see Chapter 2.4.1). The water valve control unit used in this experiment was designed by the author, which has been detailed in Chapter 2.4.2. Each LWS unit corresponds to a water valve and a main waterpipe. The drippers (2-Litre water per hour) used for automatic irrigation were installed in the root area of each plant. Each LWS unit had 15 drippers, so there would be 180 drippers for a each city in total and 360 for the research as a whole.

3.1.2 Data Collection and Statistical Approaches

The meteorological data about Sheffield and Jingmen used for analysis came from weather stations near the experiment field (see Chapter 2.7.3). Meteorological data obtained from the bureau database consist of: 1) average daily air temperature at 2 metres, 2) average daily relative humidity at 2 metres, 3) average daily precipitation and 4) average daily pressure. Those data were extracted every 1 minute and were stored every 10 minutes. The data of moisture content of growing media was measured by SM150T Soil Moisture Sensor (SMS) (moisture accuracy of ± 3% and the built-in temperature sensor achieves ± 0.5°C, Delta-T Devices Ltd, London, UK) which placed in the growing media at the centre of each LWS unit (see Chapter 2.7.3). For each city (Sheffield and Jingmen), there were 12 SMS in total. The frequency of measurement and that of data storage were 5 seconds and 1 minute, respectively.

The physiological data about plant growth focused on four different indicators, namely 1) the size of plant, 2) the number of stems, 3) the number of leaves and 4) the number of flowers. Measurements were made manually with Tape measure, 5m (accuracy 1 mm, B&Q, Eastleigh, Hampshire, UK) at noon every 15 days. Measurement dates are listed as following: 1, 15, 31 May and 15, 30 June (Phase 1); 1, 15 31 July and 15, 31 August (Phase 2); 1, 15, 30 September and 15, 31 October (Phase 3). Plant growth performance was estimated qualitatively, by observing the plant's growth and health (signs of dead leaves or flowers) as well as measuring its physical features. This was done through a non-destructive method to minimise any adverse impacts on the plants. The plants were photographed on the same day the plants were measured using a same camera model in two experiential sites (Canon EOS 60D) (details in Chapter 2.7.2). All measurement data were stored in the conclusion form (see Table 2.3 and 2.5 in Chapter 2.7).

Statistical Approaches

Data sets from UK and China and for different species was dealt with separately. A Repeated Measures ANOVA (IBM® SPSS® Statistics 25) was used to determine significance between level of irrigation and time on key growth / quality parameters. To discuss whether there is interactive effect among the other three independent variables of irrigation treatment, location, and time for each plant species separately. In order to attenuate the effect of plant's original height on the experimental results, all indicators of the plant growth were recorded and analysed in the relative increase in growth instead of the actual absolute height. Data that used in ANOVA were transformed by using the 'LG10 (max+1-x)' function, which retains the "negative number" (i.e. plant dieback) in order to ensure the normal distribution. The table of Mauchly's Test of Sphericity shows whether the data satisfies the spherical test. Data that do not meet the spherical test was corrected, using the Greenhouse-Geisser Correction for ($\varepsilon < 0.75$) or Huynd-Feldt ($\varepsilon > 0.75$). The corrected data are then examined with the Tests of Within-subjects Effects so as to obtain the importance of each factor. The statistical difference levels generated from Pairwise Comparisons were presented on Figures and Tables as letters (e.g., Fig 3.1), with mean values showing significant difference being represented by different lowercase letters. Kruskal-Wallis H test is used to analyse the difference between plant aesthetic performance by irrigation treatments because the dependent variable of plant's aesthetic rating is an ordered classification variable. The multiple comparisons of means were obtained using the Bonferroni test due to the number of comparisons is small (only 5 times) and the potential unequal sample sizes (e.g., plants dead).

Simple Linear Regression (IBM® SPSS® Statistics 25) was used to analyse the relationships between climatic factors and plant development. After finishing collecting the meteorological data of three phases (six months in total), the mean value of data collected in each phase is first analysed and further drawn into graphs showing the change (by Microsoft® Excel 2020). Pearson Correlation Analysis was used for the correlation between the indicators of plant size and the performance of plant growth because all these data belong to continuous variables. For correlation between plant aesthetic rating and growth performance, Kendall's tau-b Correlation Coefficient was chosen because all variables involved are ordinal categorical variables. A correlation coefficient (r) measures the strength of a linear association between two variables and ranges between -1 (perfect negative correlation) to 1 (perfect positive correlation) (Cohen, 1992).

All the graphs below use the transformed data to make it easier for the reader to understand. An alpha level if 0.05 was used for all statistical analysis.

3.2 RESULTS

3.2.1 *Vinca major* 'Variegata'

Vinca – Jingmen, China

1）The changes of plant height (extension growth)

In Jingmen, there were significant differences noted in the change of *Vinca*'s height in all phases ($p < 0.05$) (Fig 3.1). Overall, plants in all irrigation treatments grew much more vigorously during the third phase than in the two previous occasions.

At each phase, however, treatment effects were noted. During the first phase, *Vinca* in the wet treatment grew to a greater extent than that under the dry and the medium treatments. During the second phase, the plants in the medium treatment had the greatest growth, but generally the growing rates were slow compared to Phase 1 and 3. During the third phase, there was no significant difference noted before 15 days ($p > 0.05$, Bonferroni), but by the end of the experiment the plants on the wet and medium treatments had significantly outgrown those on the dry treatment ($p < 0.05$) (Fig 3.1).

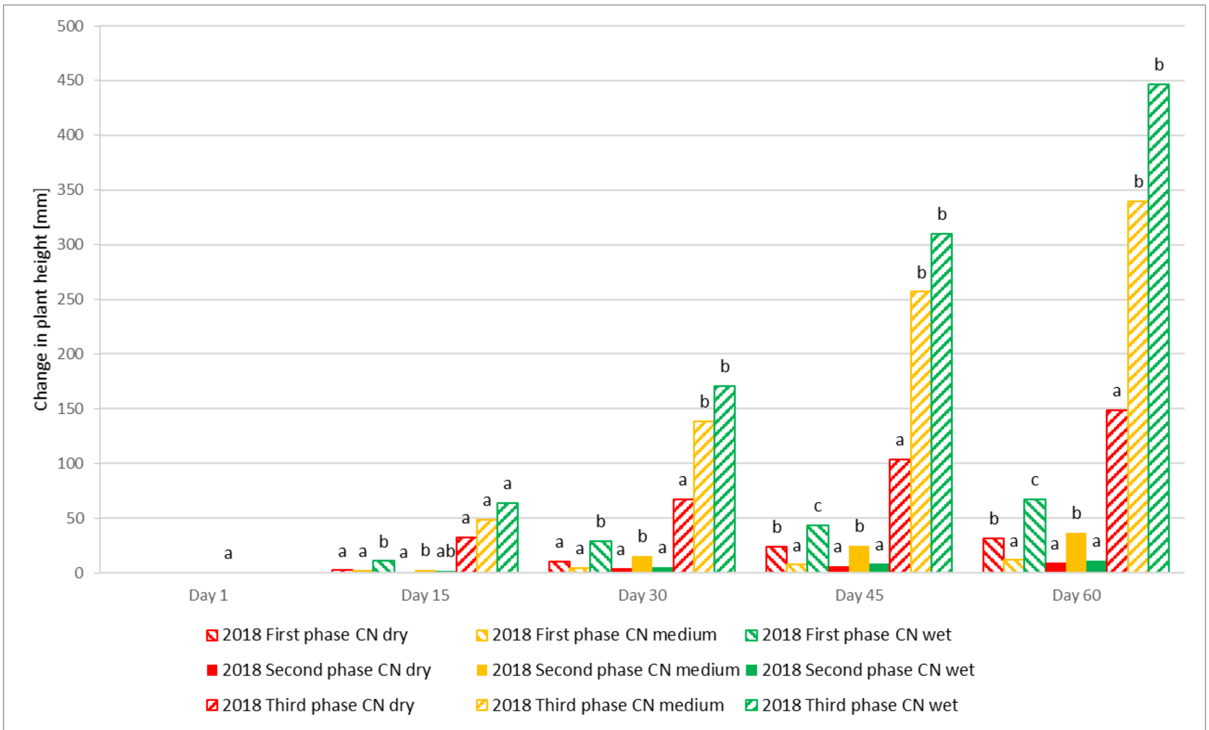

Figure 3.1 The mean change in plant height of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread (lateral growth)

Plant spread was generally the lowest in second phase, although growth was respectable in the medium irrigation treatment, by the end of the 60 days (Fig 3.2). Dieback was evident in the dry treatment during second phase. Spread was the greatest overall in the last phase (Phase 3), but there was no significant effect due to irrigation treatment ($p > 0.05$). In contrast, in first phase, plant spread was significantly greater in the wet treatment than that in the medium and dry ($p < 0.05$) (Fig 3.2).

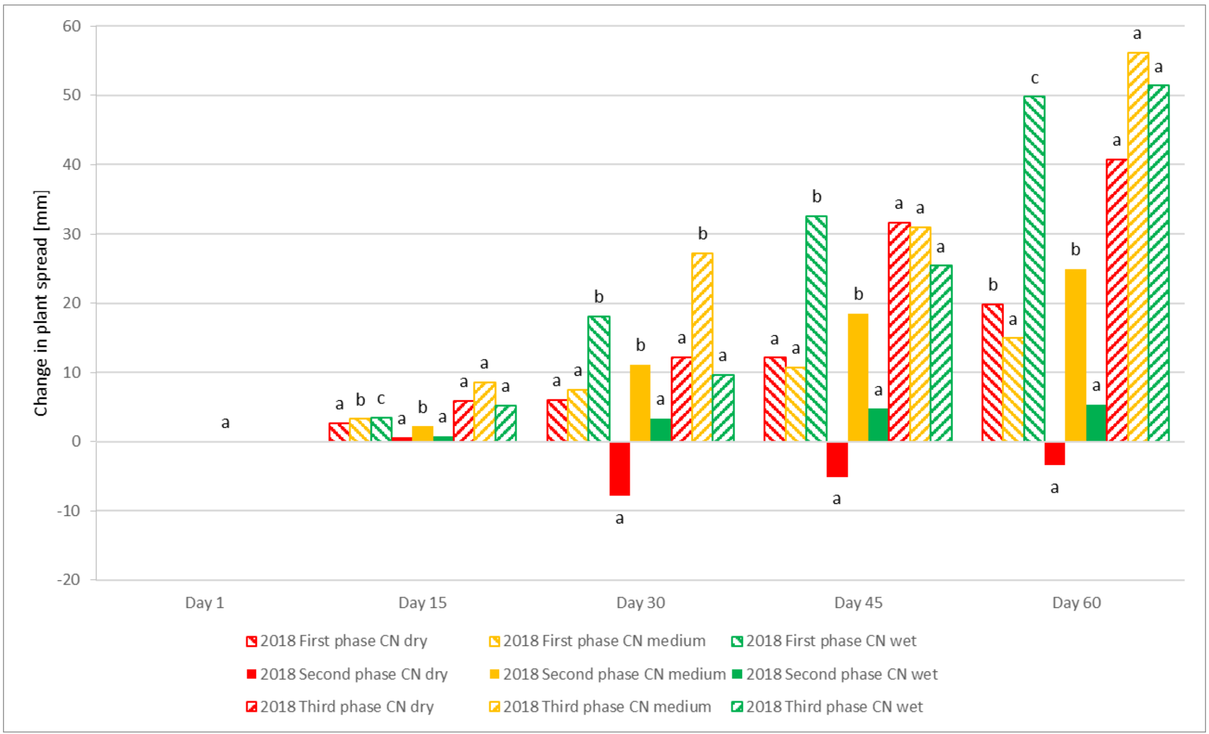

Figure 3.2 The mean change in plant spread of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3） The changes of number of plant leaves

The wet treatment in phase 1 and phase 3, (which corresponded with good plant spread), increased the number of leaves present by the end of each experiment, i.e., day 60 (Fig 3.3). Wet treatment during the third phase also corresponded with high numbers of large leaves (24.7 per plant, Table 3.2) compared to other irrigation treatments at this time ($p < 0.05$). Again though, during second phase overall leaf number was optimised by the medium wetting treatment ($p < 0.05$).

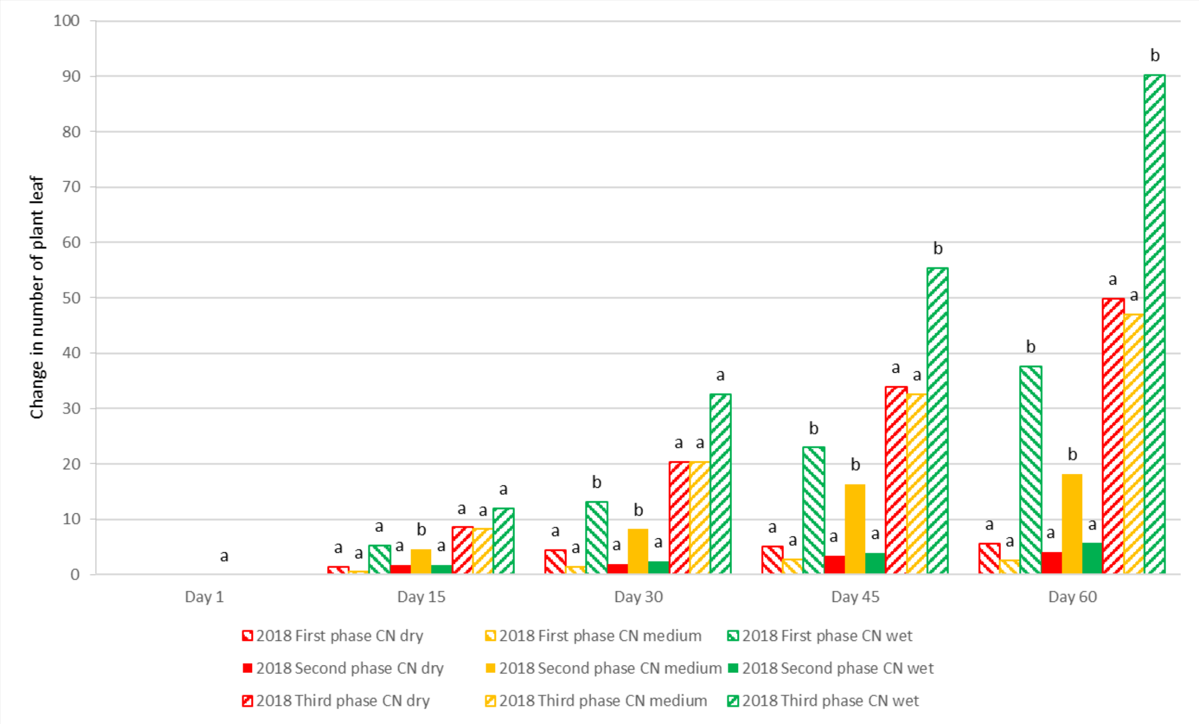

Figure 3.3 The mean change in number of plant leaves of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.2 The mean change in numbers of different size of plant leaves of *Vinca major* 'Variegata' under different irrigation treatments in the Jingmen, China (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase CN dry	5.60	1.82	1.53	0.56	-1.07	1.22	5.13	1.22
2018 First phase CN medium	2.53	2.13	1.73	1.35	-2.87	2.21	3.67	1.34
2018 First phase CN wet	37.60	2.90	8.67	2.01	10.53	2.12	18.40	1.03
2018 Second phase CN dry	4.13	1.12	0.33	0.71	-0.73	0.82	4.53	1.02
2018 Second phase CN medium	18.13	3.41	4.67	1.62	3.87	1.67	9.60	1.68
2018 Second phase CN wet	5.67	2.73	1.60	0.65	-1.33	1.46	5.40	2.24
2018 Third phase CN dry	49.87	5.18	6.93	1.83	28.67	4.07	14.27	2.37
2018 Third phase CN medium	47.00	8.84	21.40	5.10	17.13	2.95	8.47	3.93
2018 Third phase CN wet	90.20	9.44	39.60	6.37	36.40	4.51	14.20	2.78

4） The changes of plant aesthetic ratings

Plant quality was deemed respectable in the first and last phases of the experiments, but plant quality deteriorated during the second phase (across all irrigation treatments) (Fig 3.4). During this second phase, damage was significantly less in the medium irrigated plants ($p < 0.05$). In contrast, the wet region optimised plant quality in the first phase ($p < 0.05$), but there were no significant effects due to irrigation in the last phase ($p > 0.05$). From Fig 3.5, it could be seen that the rating of the second phase is lower than that of the other two phases, but the average aesthetic rating tells that the plants show similar looking in the first and second phases.

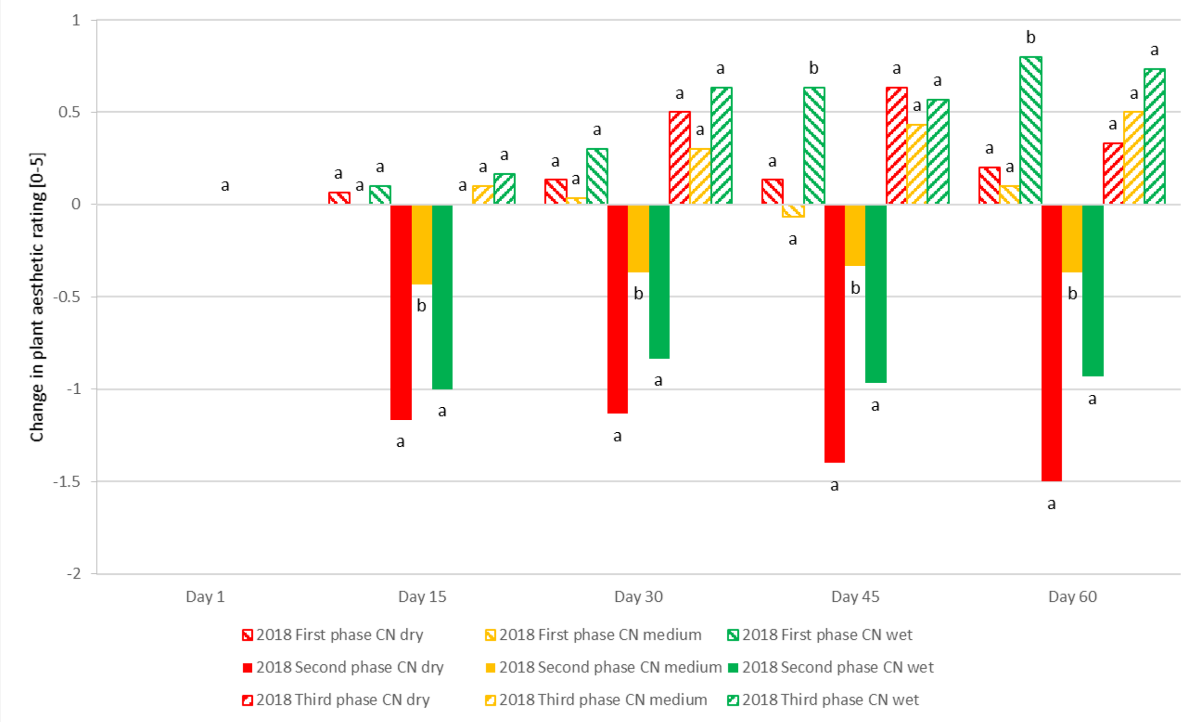

Figure 3.4 The mean change in plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

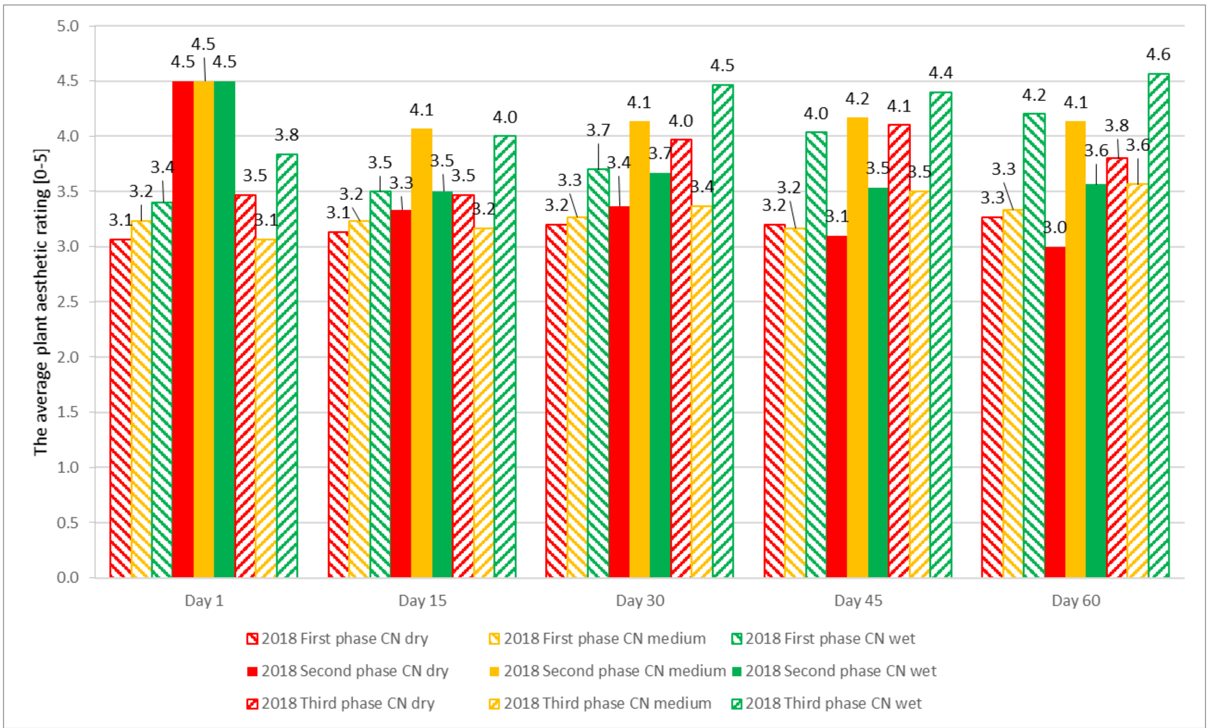

Figure 3.5 The mean value of plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp1. in 2018)

***Vinca* – Sheffield, the United Kingdom**

1）The changes of plant height (extension growth)

In Sheffield, there were significant differences noted in the change of *Vinca*’s height in the second and third phases (Fig 3.6). Overall, plants under all treatments grew much more vigorously during the first phase than they did in the two later phases.

Growth in the first phase was the greatest overall, but no differences in treatment were evident based on water supply ($p < 0.05$) (Fig 3.6). During the second phase, plants under the wet treatment significantly out-grew those under the medium and dry ($p < 0.05$). However, this was not the case in the third phase, when the wet treatment was associated with plant dieback, and the optimum treatment at this time was the medium watering regime ($p < 0.05$), but overall growth was much curtailed compared to earlier in the first phase.

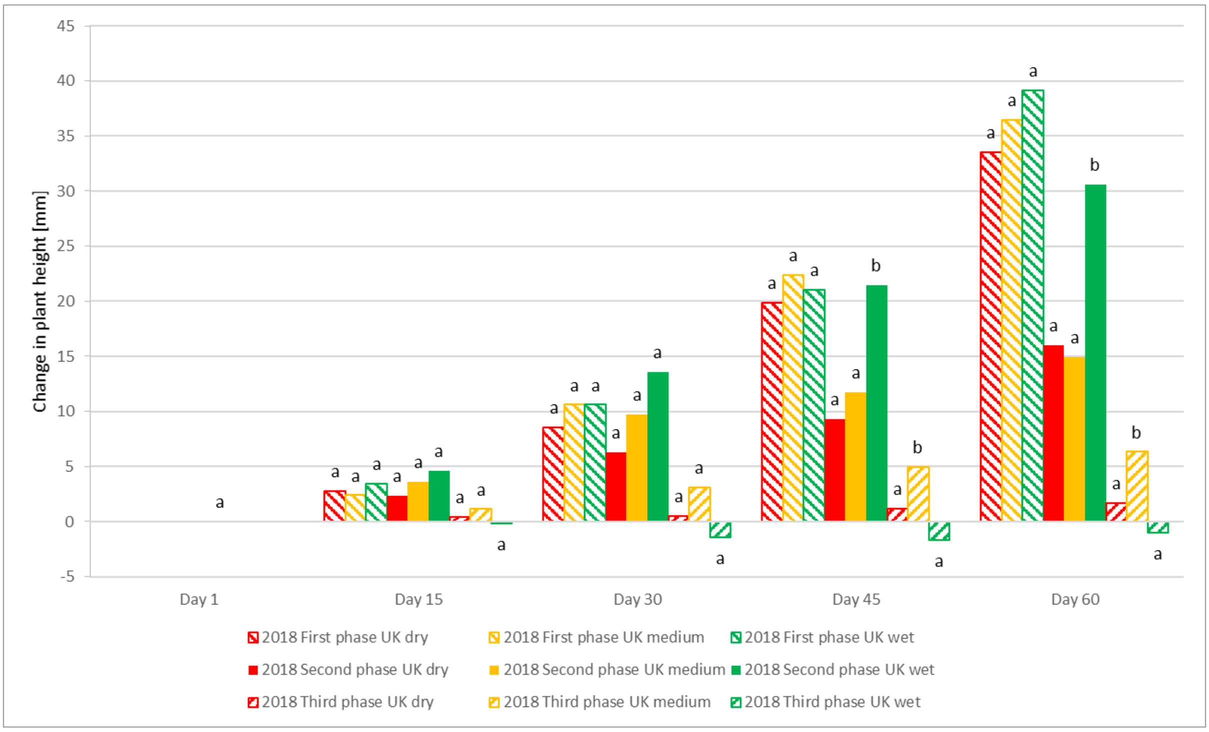

Figure 3.6 The mean change in plant height of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread (lateral growth)

Generally, the plant spread was the greatest in the first phase, with the wet treatment beating the medium and the dry treatments ($p < 0.05$) by the end of the 60 days (Fig 3.7). In contrast, the plant spread was the lowest in the second phase. Although the growth was proper under the medium irrigation treatment in the end of the 60 days ($p < 0.05$), the dieback was evident in both the dry and the wet treatments during the second phase. During the third phase, the plant spread was significantly greater under the dry and the wet treatment compared to that under the medium ($p < 0.05$).

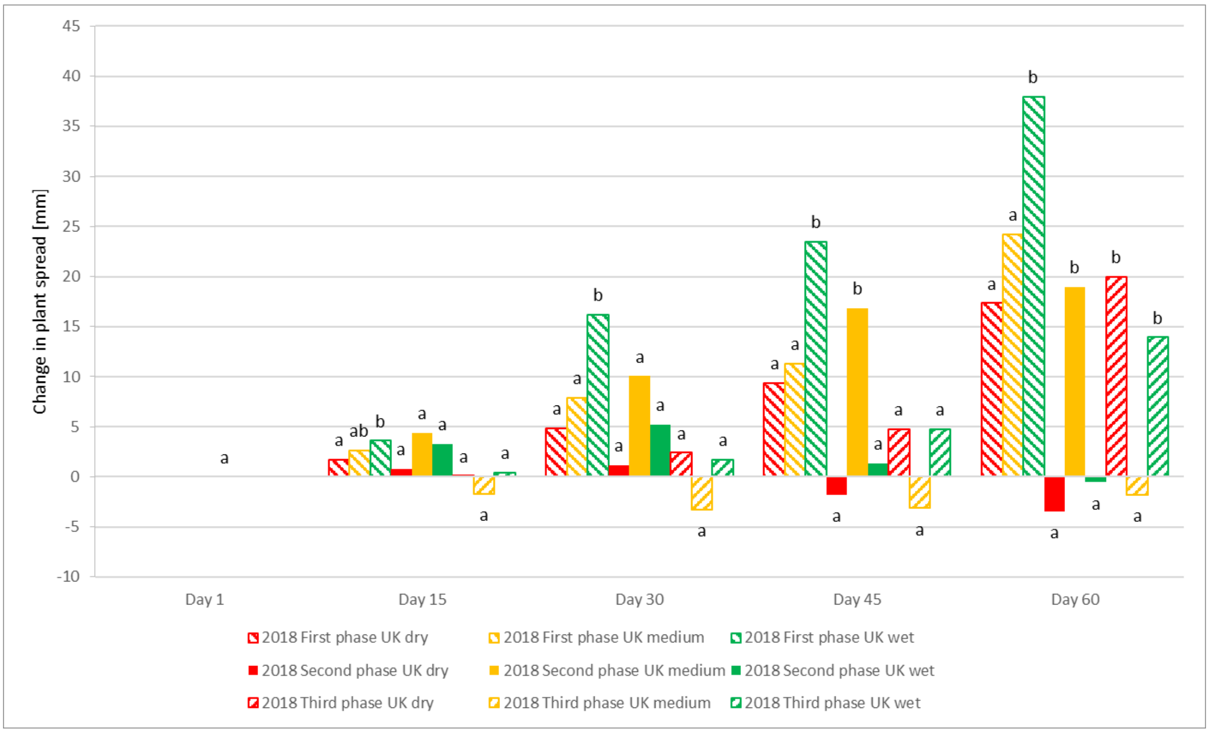

Figure 3.7 The mean change in plant spread of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

The development of plant leaves was generally the lowest in the first phase. All treatments caused plants to lose their leaves, especially the dry treatment ($p < 0.05$) (Fig 3.8). This treatment had much fewer leaves by the end of the 60 days. Dry and medium treatment during the second phase corresponded with high numbers of large leaves (27.4 per plant, Table 3.3) compared to the wet treatment did at this time ($p < 0.05$). However, during the third phase, overall leaf number was optimised by the wet treatment compared to others ($p < 0.05$).

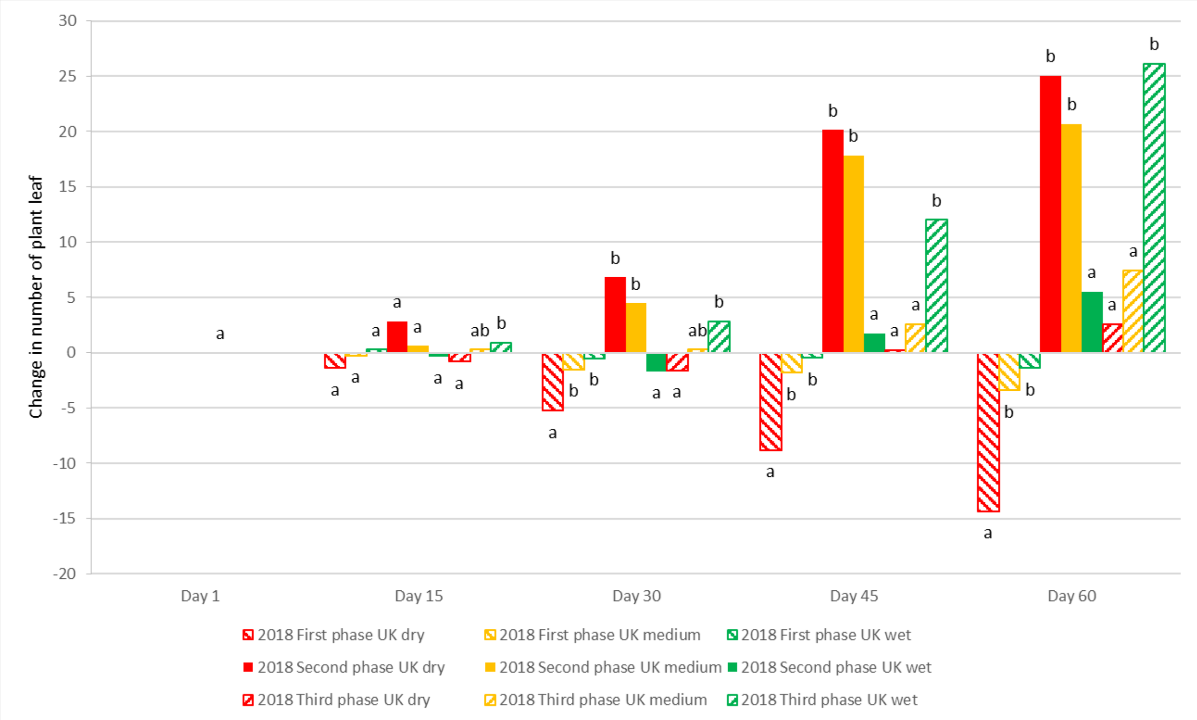

Figure 3.8 The mean change in number of plant leaves of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.3 The mean change in numbers of different size of plant leaves of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase UK dry	-14.33	2.47	-8.80	0.91	-1.07	2.02	-4.47	1.37
2018 First Phase UK medium	-3.40	5.55	1.73	2.14	-6.13	4.88	1.00	1.42
2018 First phase UK wet	-1.40	3.57	-4.00	1.50	-0.13	2.69	2.73	1.82
2018 Second phase UK dry	25.07	4.41	0.27	1.34	20.53	3.86	4.27	1.41
2018 Second phase UK medium	20.67	3.49	-0.13	1.40	15.87	3.12	4.93	1.33
2018 Second phase UK wet	5.53	2.22	-0.47	0.57	3.27	1.92	2.73	1.22
2018 Third phase UK dry	2.60	2.13	0.87	1.41	-0.47	2.56	2.20	0.55
2018 Third phase UK medium	7.47	2.51	0.33	1.28	4.73	2.81	2.40	0.95
2018 Third phase UK wet	26.13	4.27	2.13	1.46	22.87	3.78	1.13	0.83

4) The changes of plant aesthetic ratings

Plant quality was deemed respectable in the second and last phases of the experiment, but plant quality deteriorated during the first phase under the dry irrigation treatment (Fig 3.9). In contrast, the middle region optimized plant quality in the third phase ($p < 0.05$), but there were no significant effects due to irrigation in the second phase ($p > 0.05$). Although the rating increase in the second phase is lower than that in the first phase, the average rating (Fig 3.10) shows that there is no significant difference between the two.

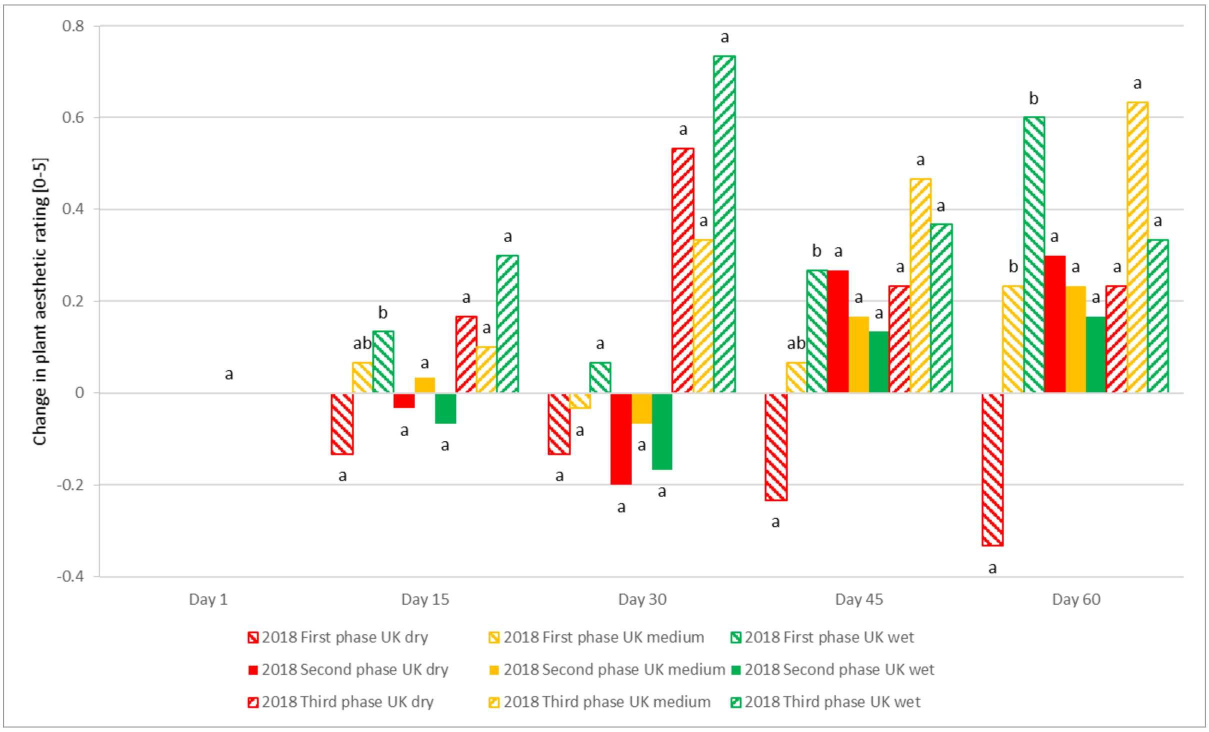

Figure 3.9 The mean change in plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

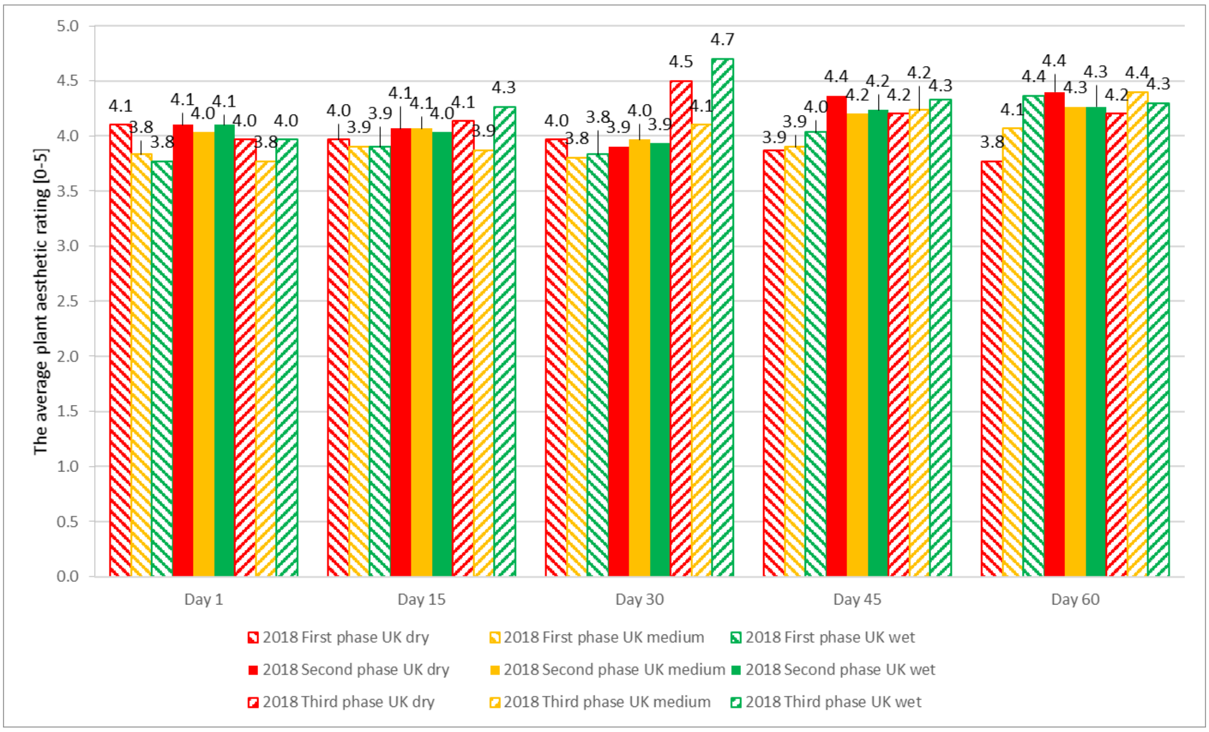

Figure 3.10 The mean value of plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

3.2.2 *Hosta* 'Blue Mouse Ears'

***Hosta* – Jingmen, China**

1）The changes of plant height (extension growth)

In Jingmen, there were significant differences noted in the change of *Hosta*'s height in all phases ($p < 0.05$) (Fig 3.11).

Plant height was overall the greatest in the first phase. It was the plants under the dry and the medium treatments significantly out-grew those under the wet one ($p < 0.05$). This was not the case however, in second phase, when the dry and medium treatment was significantly less than the wet and the dieback appeared under the medium ($p < 0.05$). The plant height reduced during the third phase, but the reduction was significantly less in the medium and wet irrigated plants ($p < 0.05$).

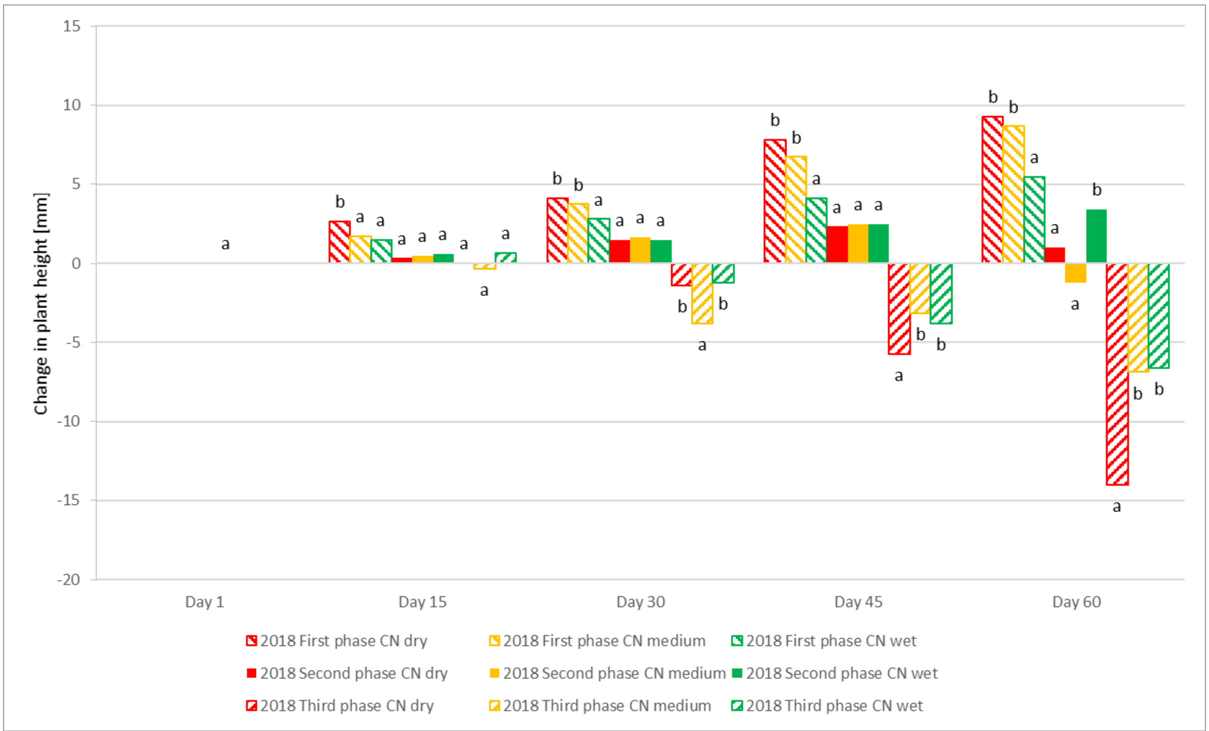

Figure 3.11 The mean change in plant height of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread (lateral growth)

Plant spread was generally the greatest in the first phase, and the growth was respectable in the dry and medium irrigation treatment ($p < 0.05$) by the end of the 60 days (Fig 3.12). However, dieback was evident both in the middle and the third phase under all treatments. During this second phase, damage was significantly less in the dry and medium irrigated plants ($p < 0.05$). In contrast, the wet treatment resulted in a significant reduction in plant spread compared to the other treatments ($p < 0.05$).

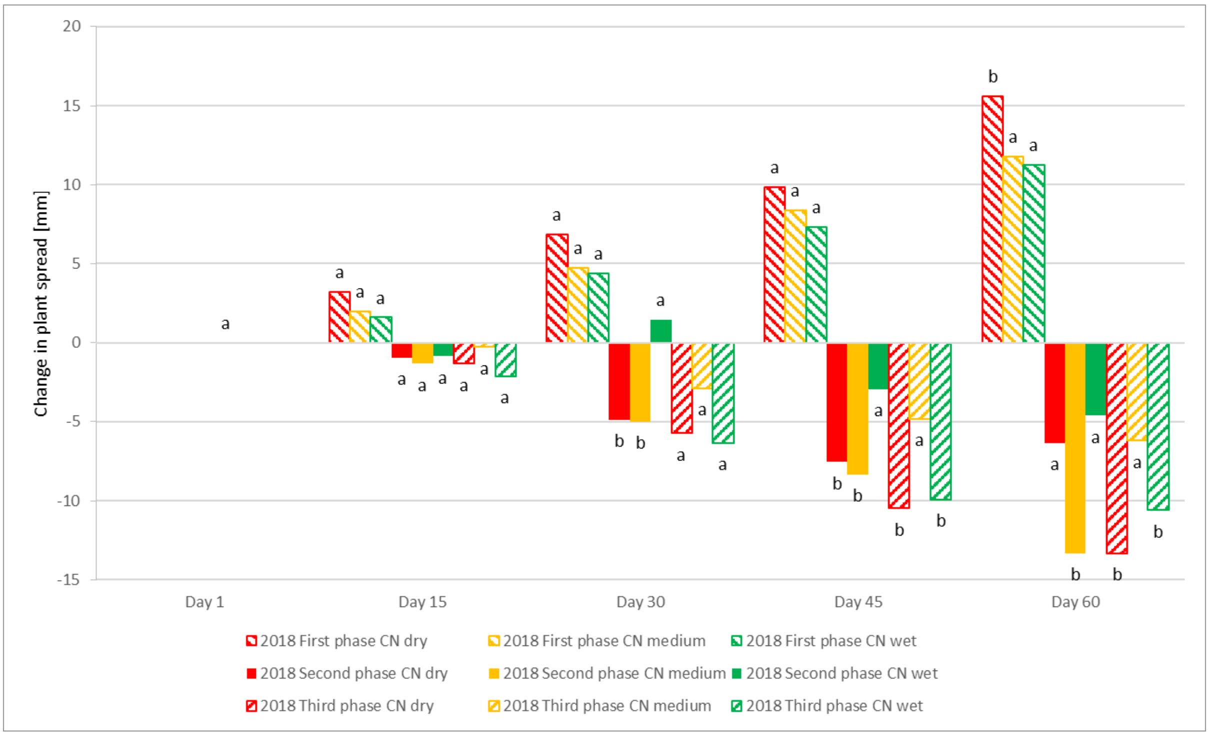

Figure 3.12 The mean change in plant spread of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

The number of leaves increased under some treatments in the first and second phase, whereas in the last phase leaf number decreased after 60 days (Fig 3.13), with any new growth being associated with small numbers of small leaves (Table 3.4). There were treatment differences at different times – with wet regime detrimental in first phase and the dry treatment sub-optimal in second phase ($p < 0.05$).

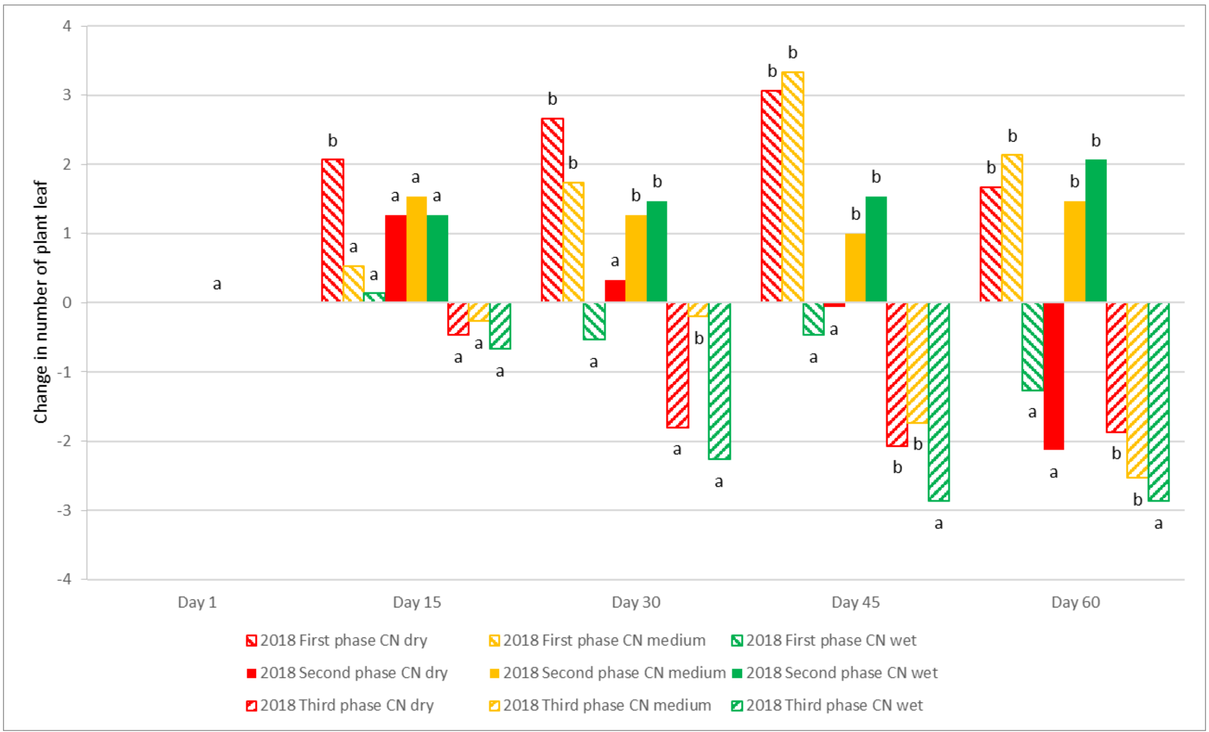

Figure 3.13 The mean change in number of plant leaves of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.4 The mean change in numbers of different size of plant leaves of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in the Jingmen, China (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase UK dry	1.67	0.76	-0.73	0.67	1.80	0.68	0.60	0.19
2018 First Phase UK medium	2.13	0.70	-2.60	0.39	3.93	0.65	0.80	0.31
2018 First phase UK wet	-1.27	0.83	-3.33	0.81	2.27	0.68	-0.20	0.11
2018 Second phase UK dry	-2.13	0.88	-2.13	0.55	-1.00	0.70	1.00	0.20
2018 Second phase UK medium	1.47	0.41	-0.13	0.42	0.73	0.48	0.87	0.19
2018 Second phase UK wet	2.07	0.41	-0.20	0.26	0.13	0.34	2.13	0.26
2018 Third phase UK dry	-1.87	0.89	-1.87	0.54	-1.07	0.38	1.07	0.46
2018 Third phase UK medium	-2.53	1.37	-2.73	0.77	-0.33	0.90	0.53	0.35
2018 Third phase UK wet	-2.87	1.00	-3.47	0.71	-0.53	0.76	1.13	0.58

4) The changes of plant aesthetic ratings

Plant quality was deemed respectable in the first phase of the experiment, but plant quality deteriorated during the second and third phases (Fig 3.14). During this second phase, damage was significantly greater in the dry treatment. Dry and wet treatment during late phase also caused much more damage ($p < 0.05$). Fig 3.14 shows the slow growth of aesthetic rating in the third phase. It can be seen in Fig 3.15 that the average increase in the third phase is smaller than those in the previous two phases.

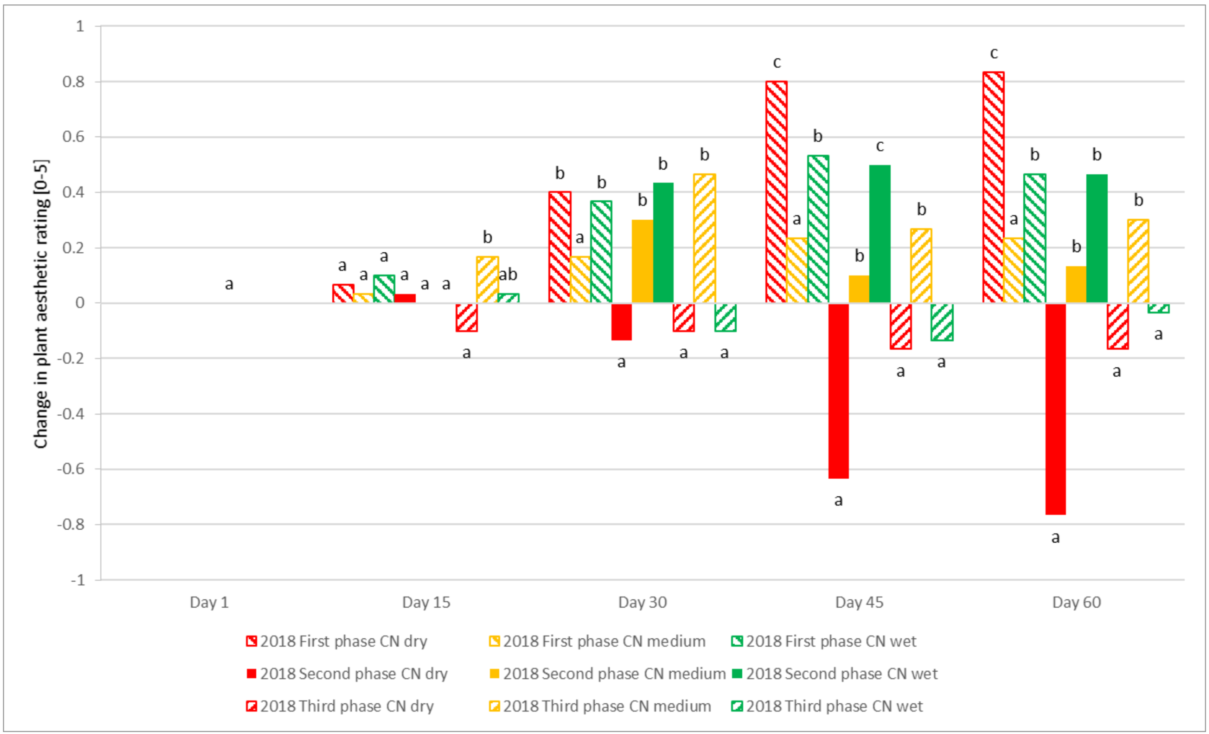

Figure 3.14 The mean change in plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

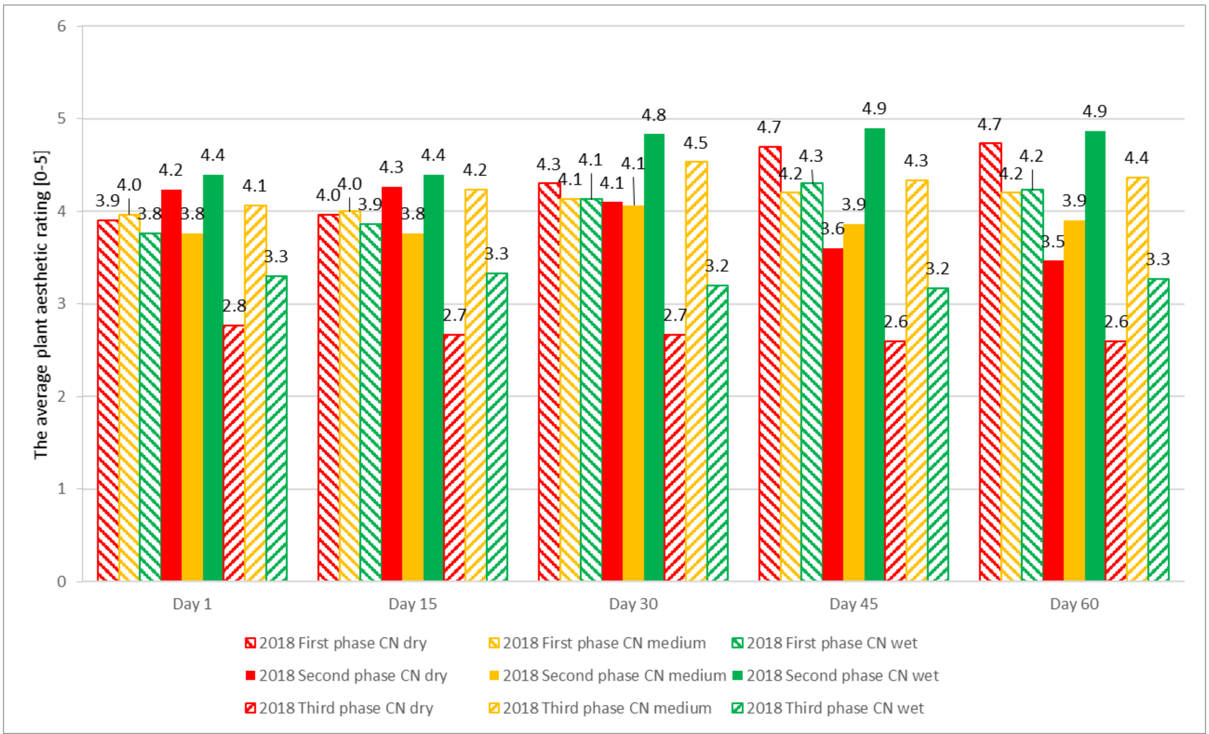

Figure 3.15 The mean value of plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen, China (Exp1. in 2018)

***Hosta* – Sheffield, United Kingdom**

1）The changes of plant height (extension growth)

In Sheffield, there were significant differences noted in the change of *Hosta*’s height in all phases ($p < 0.05$) (Fig 3.16).

Growth was overall the greatest in the first phase, and the optimum treatment at this phase was the wet watering regime ($p < 0.05$). This was not the case however, in second phase, when the wet treatment was associated with a significant net loss of growth ($p < 0.05$) (i.e., die-back). During the third phase (autumn), dieback was evident in the dry and medium treatment (Fig 3.16). Wet irrigation, however, is the optimal irrigation option at this point ($p < 0.05$).

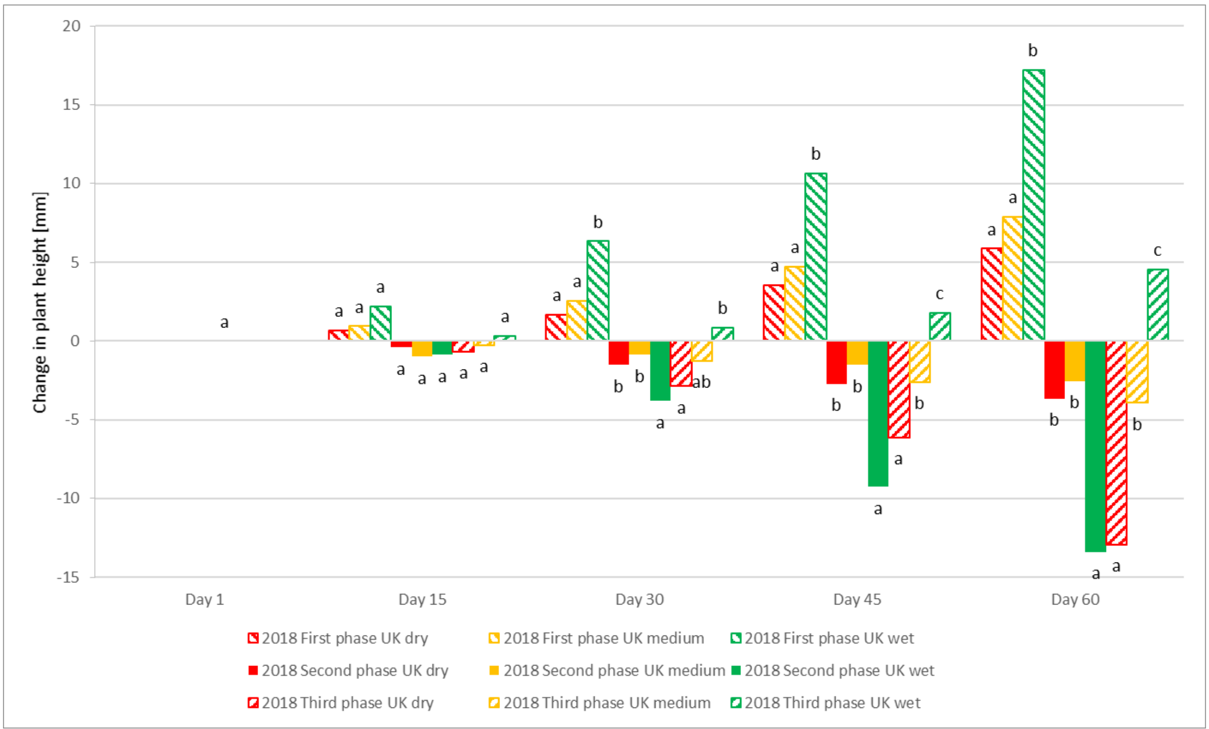

Figure 3.16 The mean change in plant height of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread (lateral growth)

Plant spread was generally the greatest in first phase, and the growth was respectable in the dry and wet irrigation treatment ($p < 0.05$) by the end of the 60 days. Dieback was evident in the wet treatment during the second phase. All treatments suffered die-back in the late phase, this being most acute in the dry treatment ($p < 0.05$) (Fig 3.17).

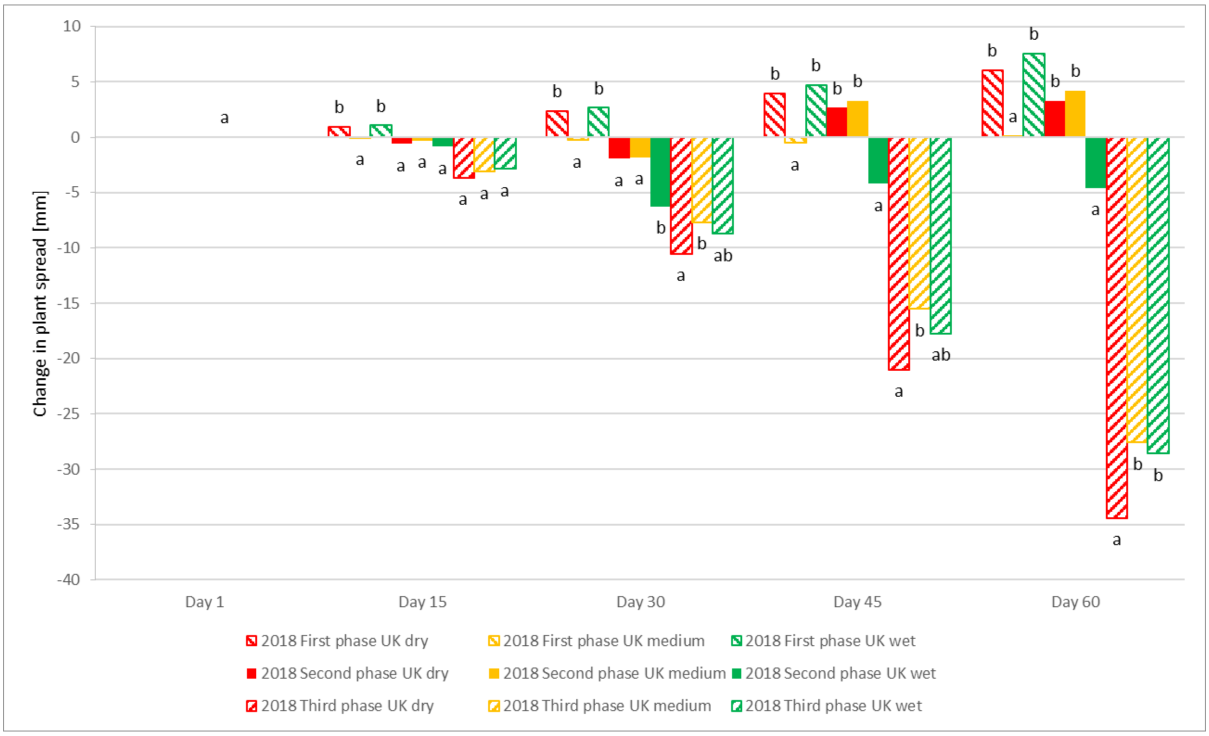

Figure 3.17 The mean change in plant spread of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

A net gain in leaf number (mostly those at a larger size, Table 3.5) was only evident in the second phase and with the dry and medium irrigation treatments alone ($p < 0.05$). All other treatments resulted in a net loss of leaves, particularly so with in the medium treatment in early phase ($p < 0.05$) (Fig 3.18). In the third phase, dry and wet irrigation caused loss of leaves, which was no more than the loss in the first phase ($p < 0.05$). The lost leaves in the third phase were mainly of medium size. No increase was seen in the number of leaves of small size in all phases (Table 3.5).

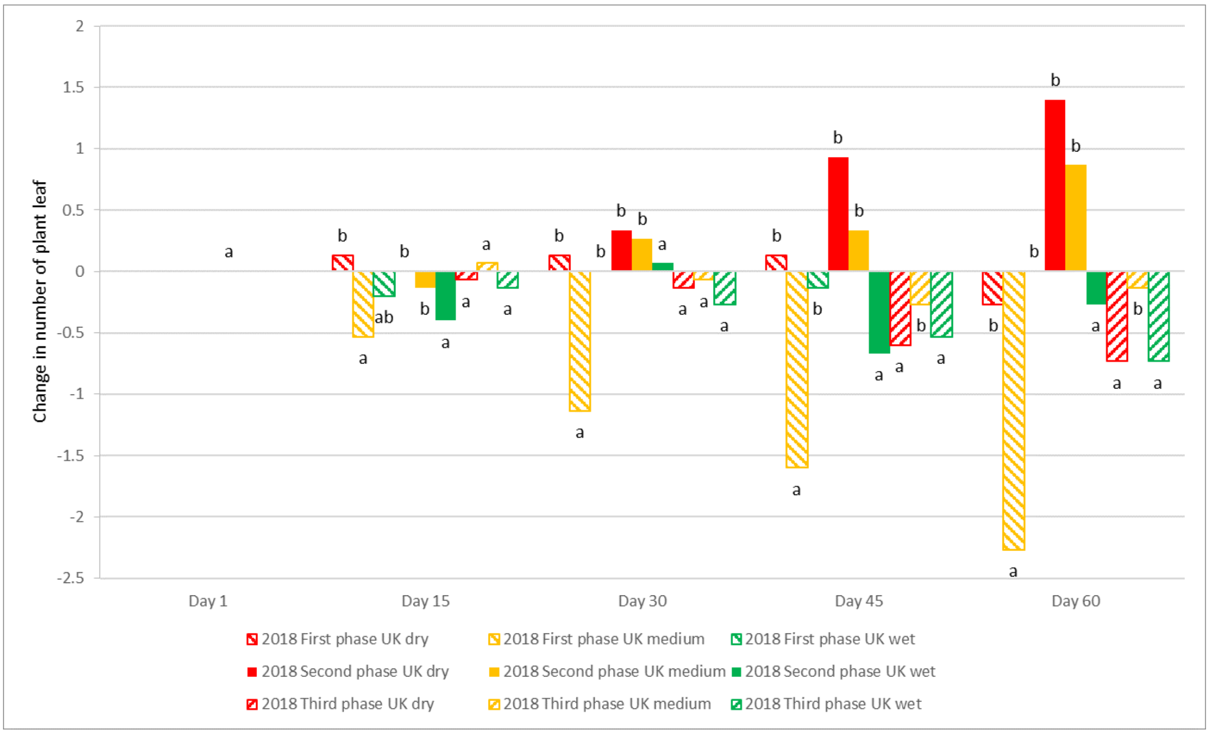

Figure 3.18 The mean change in number of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.5 The mean change in numbers of different size of plant leaves of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase UK dry	-0.27	0.54	-0.47	0.39	0.20	0.42	0.00	0.00
2018 First Phase UK medium	-2.27	0.49	-0.27	0.18	-2.00	0.44	0.00	0.00
2018 First phase UK wet	0.00	0.76	-0.13	0.24	0.13	0.70	0.00	0.00
2018 Second phase UK dry	1.40	0.49	0.80	0.53	0.60	0.39	0.00	0.00
2018 Second phase UK medium	0.87	0.27	0.53	0.19	0.33	0.27	0.00	0.00
2018 Second phase UK wet	-0.27	0.25	-0.33	0.13	0.07	0.15	0.00	0.00
2018 Third phase UK dry	-0.73	0.23	1.33	0.42	-2.07	0.51	0.00	0.16
2018 Third phase UK medium	-0.13	0.16	1.60	0.36	-1.73	0.28	0.00	0.00
2018 Third phase UK wet	-0.73	0.45	1.40	0.83	-2.13	0.59	0.00	0.00

4） The changes of plant aesthetic ratings

Plant quality overall tends to deteriorate in this genotype. The quality is retained in terms of appearance only under the dry treatment in the first phase and the wet treatment in the second phase ($p < 0.05$) (Fig 3.19). The average rating shows a similar growing trend as the rating changes. The previous two phases have higher ratings than the third phase does (Fig 3.20). The reason why the aesthetic rating in the third phase decreases significantly is that the plants entered natural dormancy with many leaves withering.

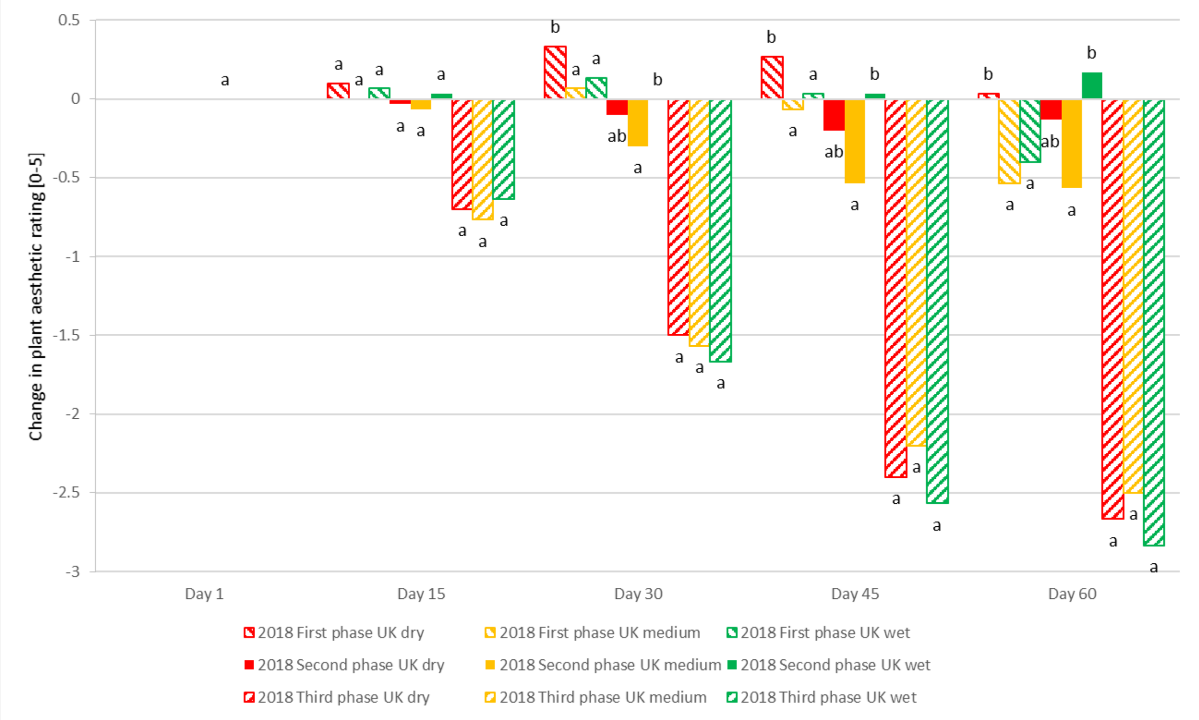

Figure 3.19 The mean change in plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

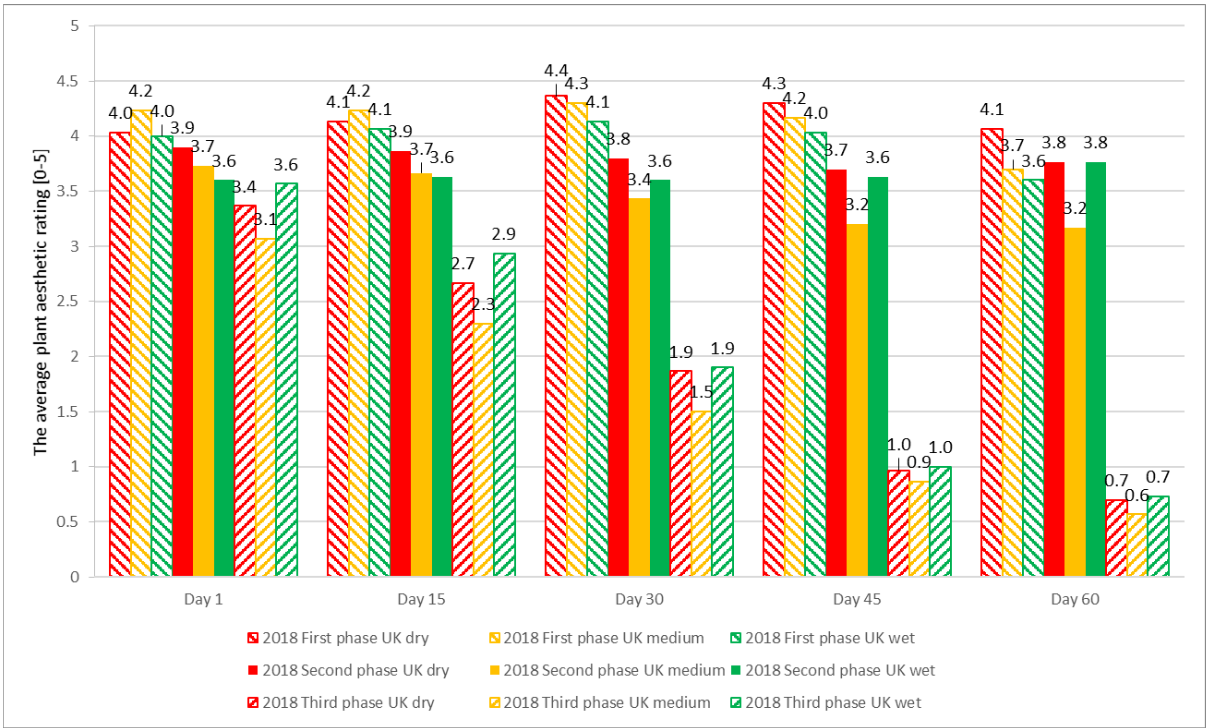

Figure 3.20 The mean value of plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

3.2.3 *Heuchera* 'Marmalade'

***Heuchera* – Jingmen, China**

1) The changes of plant height (extension growth)

Plant growth in Jingmen was better than in Sheffield. There were significant differences noted in the change of *Heuchera*'s height in the first and third phases ($p < 0.05$) (Fig 3.21).

Growth was overall the greatest in the first phase, and plants under the wet treatment, which is the optimum treatment at this time, out-grew those under the dry and the medium treatments ($p < 0.05$). This was the same case in the third phase. The height of plants under the wet treatment was significantly increased ($p < 0.05$). During the second phase, there was no evident differences in treatment based on water supply ($p > 0.05$).

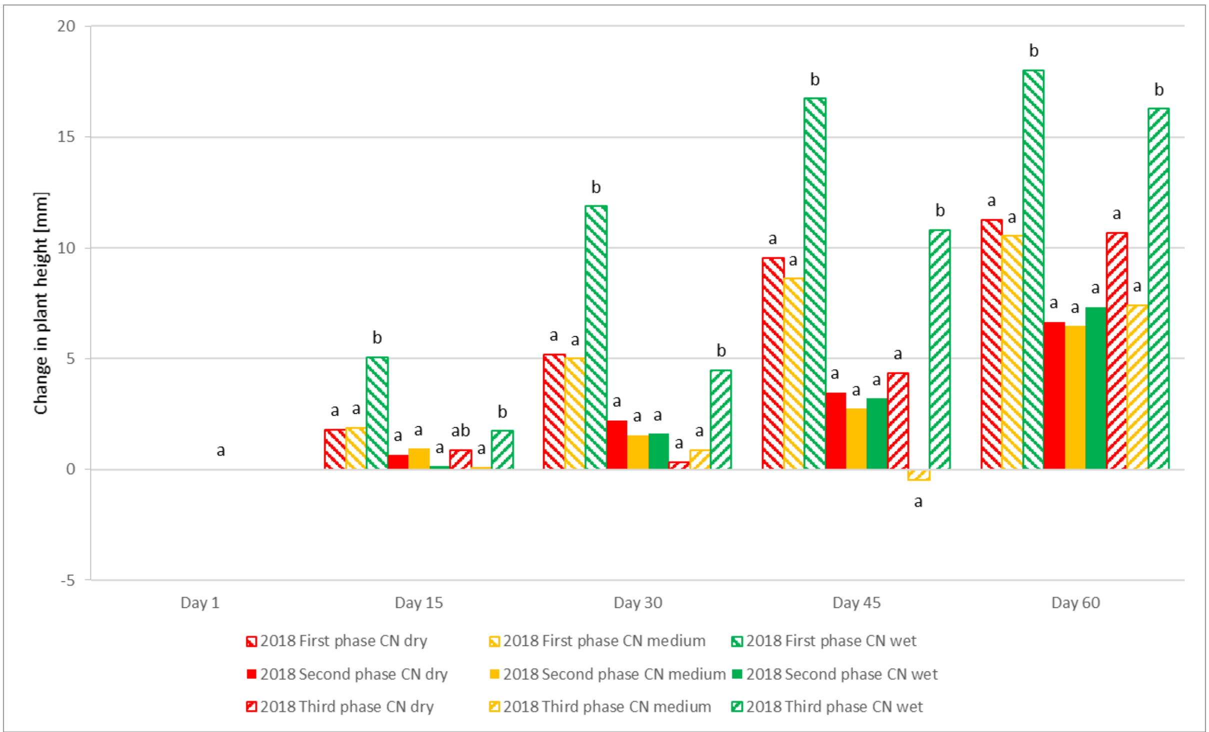

Figure 3.21 The mean change in plant height of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2) The changes of plant spread (lateral growth)

Plant spread was generally the lowest in second phase though growth was respectable under the dry irrigation treatment ($p < 0.05$) by the end of the 60 days (Fig 3.22). Dieback was evident in the wet treatment during this middle phase ($p < 0.05$). During the first phase, the plant spread was significantly greater under the wet treatment than under the medium and the dry treatment ($p < 0.05$). In contrast, in the last phase, the dry and the wet treatments boost the plant spread significantly better than the medium treatment ($p < 0.05$).

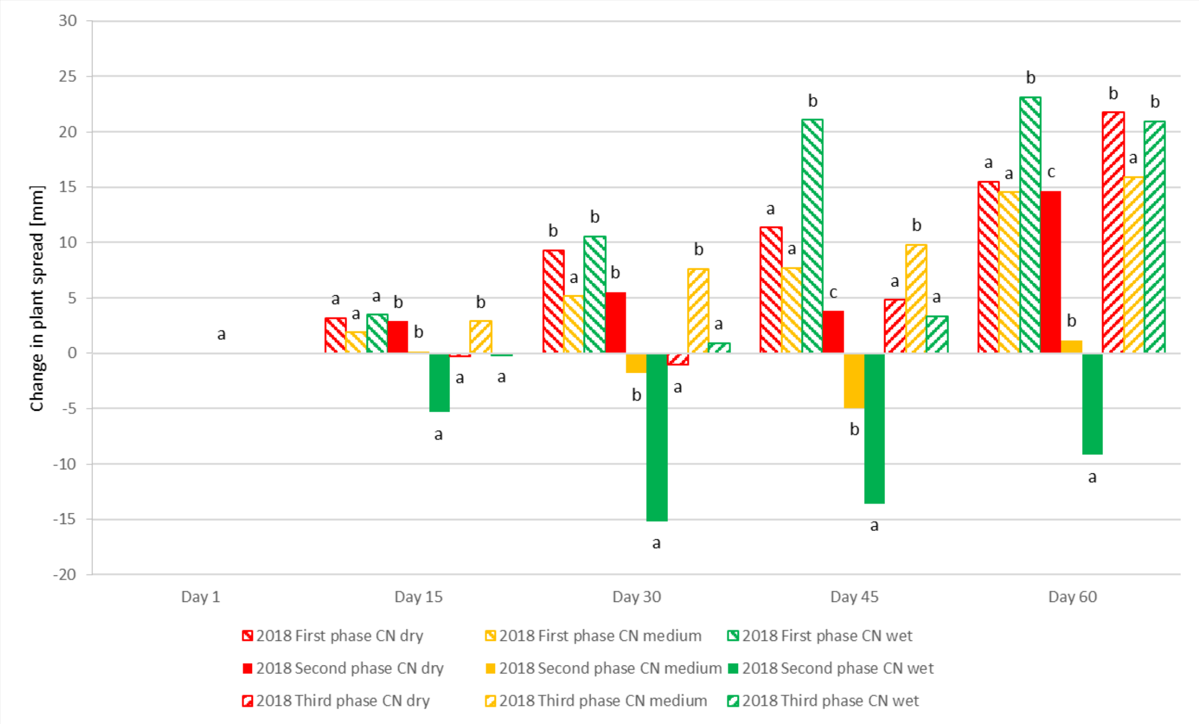

Figure 3.22 The mean change in plant spread of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

Generally, plant leaves were the fewest in the second phase, though under the dry irrigation treatment the number of leaves significantly increased ($p < 0.05$) by the end of the 60 days (Fig 3.23). In the other two treatments, dieback was evident during the second phase. The wet treatment achieves the high performance during the first and the third phase, where not only the plant spread but also the increase in the number of leaves was significant. Wet treatment during the first phase also corresponded with high number of medium (9.81 per plant) and small leaves (2.17 per plant, Table 3.6). As for the dry treatment, its optimal results are achieved during the third phase, as evidenced by the high number of large leaves (5.17 per plant).

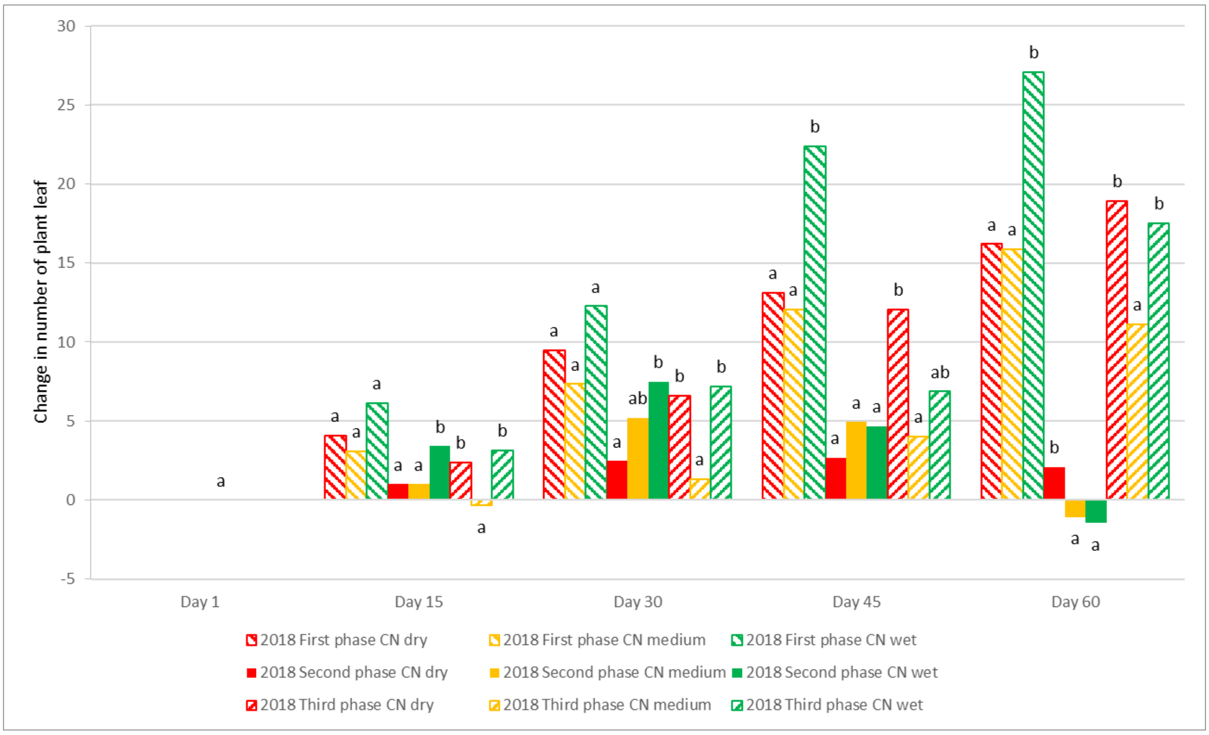

Figure 3.23 The mean change in number of plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.6 The mean change in numbers of different size of plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in the Jingmen, China (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase UK dry	16.20	1.98	8.93	1.69	7.80	1.92	-0.53	1.12
2018 First Phase UK medium	15.87	2.58	9.07	1.97	5.13	1.65	1.67	1.57
2018 First phase UK wet	27.07	3.02	10.20	1.79	12.73	4.05	4.13	1.27
2018 Second phase UK dry	2.07	1.99	2.13	2.60	-2.07	2.37	2.00	1.64
2018 Second phase UK medium	-1.07	1.80	-5.47	1.17	2.53	1.55	1.87	1.37
2018 Second phase UK wet	-1.47	1.92	-4.93	1.51	0.60	1.83	2.87	1.73
2018 Third phase UK dry	18.93	2.78	14.13	2.14	6.87	2.68	-2.07	1.62
2018 Third phase UK medium	11.13	2.92	6.93	2.15	7.40	2.88	-3.20	1.20
2018 Third phase UK wet	17.53	3.42	3.67	1.89	9.67	2.58	4.20	1.67

4) The changes of the aesthetic ratings of the plants

Plant quality was deemed respectable in the first and last phases of the experiment, but plant quality deteriorated during the second phase except for the wet treatment ($p < 0.05$) (Fig 3.24). Compared with other two phases, phase 3 had the highest aesthetic ratings under all irrigation treatments with the highest rating in dry treatment in this phase ($p < 0.05$). However, for the actual aesthetic performance (Fig 3.25), the average rating did not undergo big change and remained at a high mark (generally above 4).

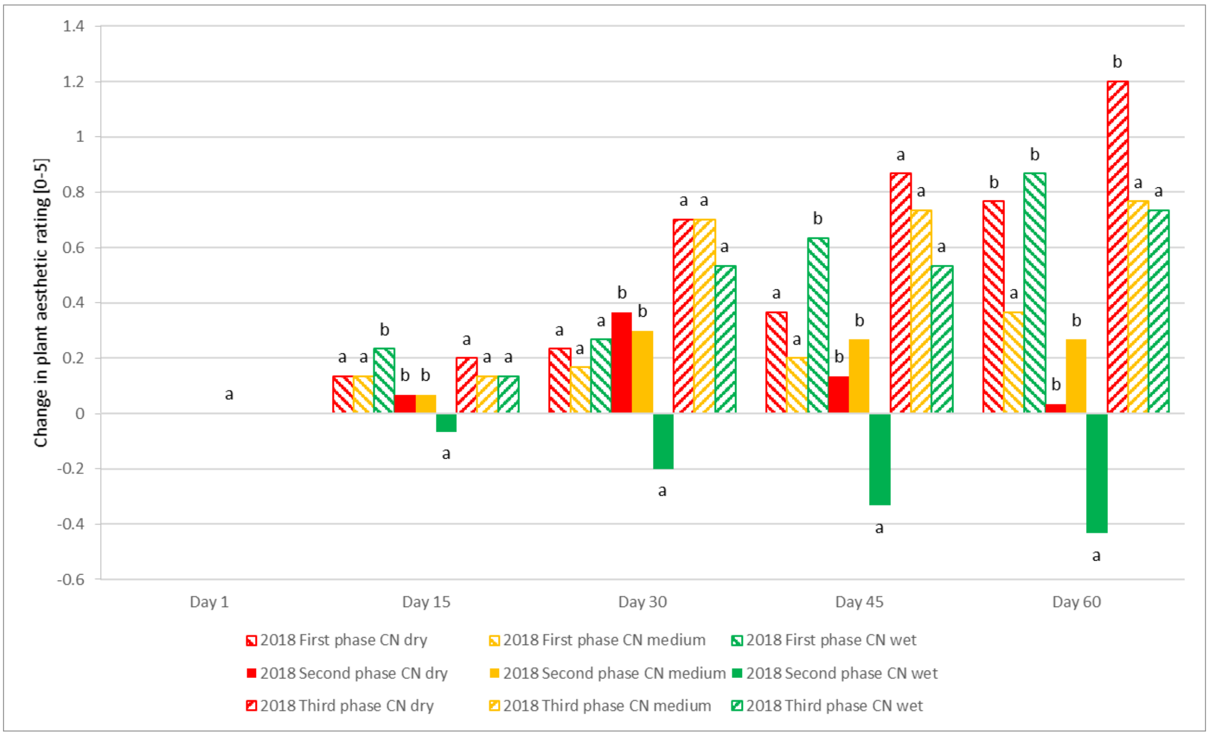

Figure 3.24 The mean change in plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

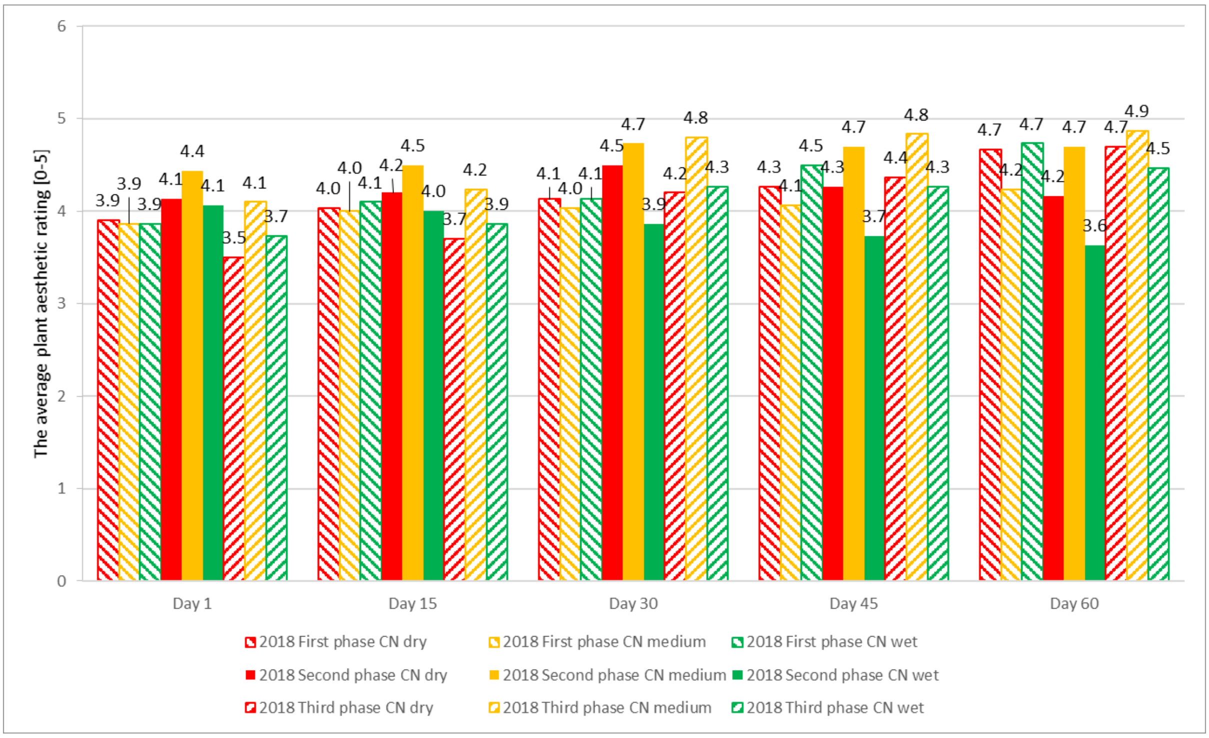

Figure 3.25 The mean value of plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen, China (Exp1. in 2018)

***Heuchera* ‘Marmalade’**

***Heuchera* – Sheffield, United Kingdom**

1）The changes of plant height (extension growth)

In Sheffield, there were significant differences noted in the change of *Heuchera*’s height in the phase 2 and phase 3 ($p < 0.05$) (Fig 3.26).

Growth was overall the greatest in the first phase, but no treatment differences were evident based on water supply ($p > 0.05$) (Fig 3.26). During the second phase, plants under the dry treatment significantly out-grew those under the medium and wet ($p < 0.05$). However, this was not the case in the third phase, when damage was significant under the dry and wet treatments.

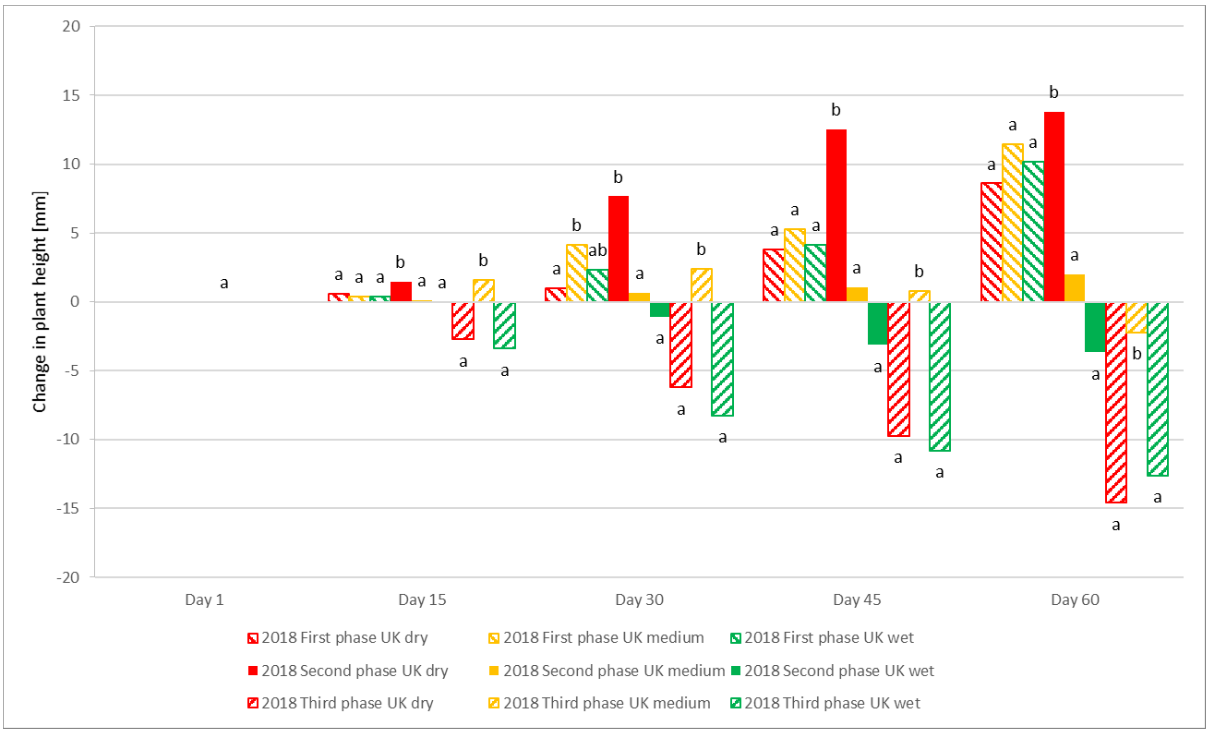

Figure 3.26 The mean change in plant height of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread (lateral growth)

Plant spread was generally the lowest in the third phase, and growth was respectable under the dry and medium irrigation treatment by the end of the 60 days (Fig 3.27). Dieback was evident in the wet treatment during this phase. Spread was encouraged under the medium irrigation treatment than those under the other treatments during all phases ($p < 0.05$).

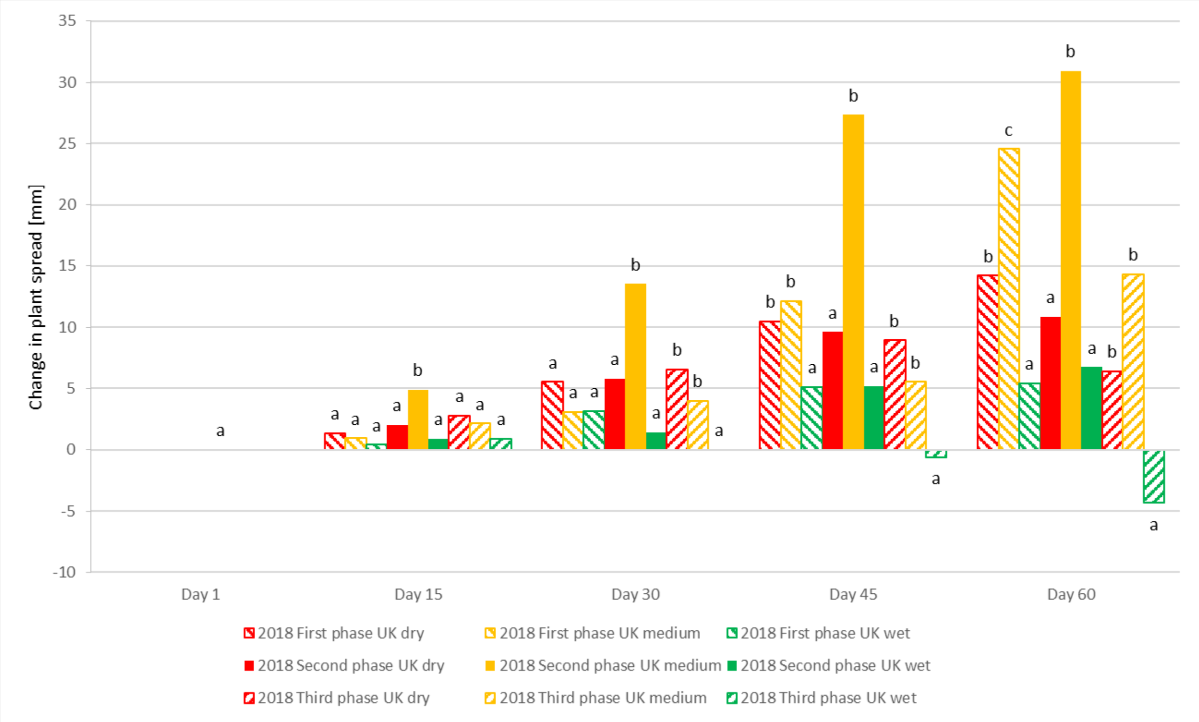

Figure 3.27 The mean change in plant spread of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3) The changes of numbers of plant leaves

Generally, the leaf development was the greatest in the second phase, where the dry and the medium treatments give the optimised productions in this regard ($p < 0.05$). These treatments also produced the greatest leaf numbers in the last phase. In contrast, the wet treatment as optimal for leaf development only in the first phase ($p < 0.05$) (Fig 3.28). Another observation is that the medium treatment led to the high number of large leaves during the second phase (3.48 per plant, Table 3.7).

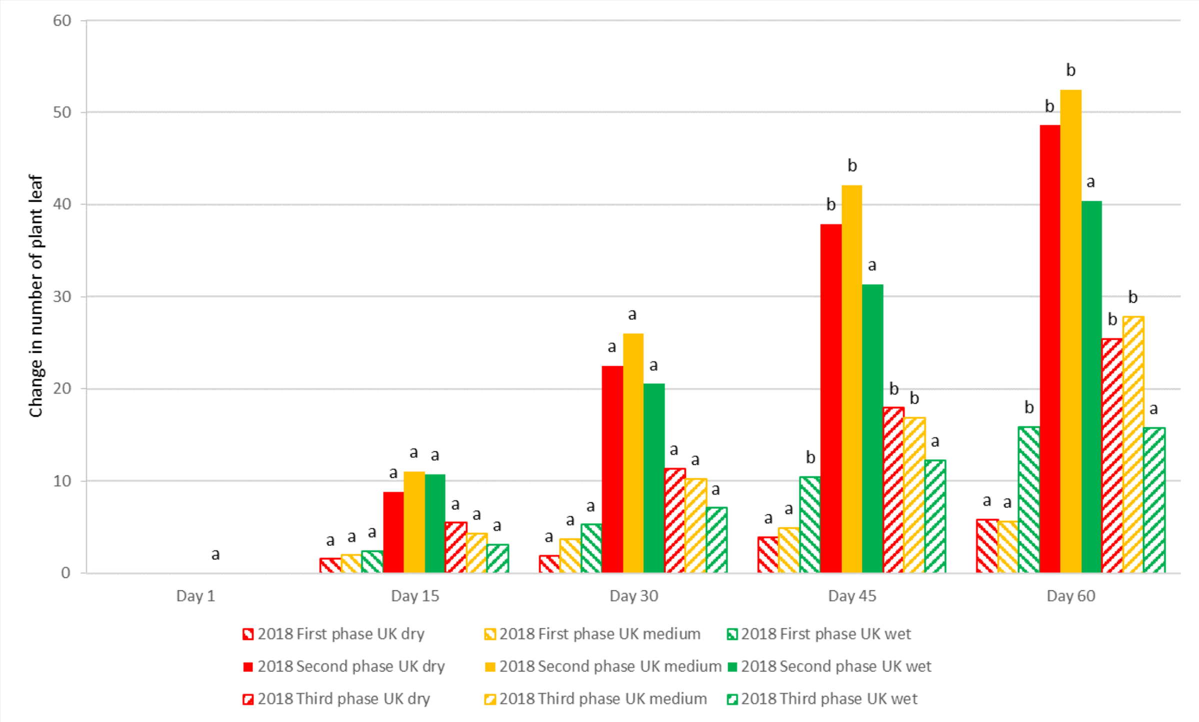

Figure 3.28 The mean change in number of plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.7 The mean change in numbers of different size of plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase UK dry	5.80	2.48	9.93	2.66	-7.87	3.67	3.73	0.63
2018 First Phase UK medium	5.60	1.87	12.60	1.20	-10.93	2.19	3.93	0.58
2018 First phase UK wet	15.87	2.19	24.27	3.30	-11.80	2.16	3.40	0.62
2018 Second phase UK dry	48.60	4.96	8.93	2.46	31.93	3.13	7.73	0.58
2018 Second phase UK medium	52.47	4.43	12.53	2.20	30.47	3.52	9.47	0.73
2018 Second phase UK wet	40.40	2.45	3.13	2.22	26.67	2.70	10.60	0.96
2018 Third phase UK dry	25.40	1.76	3.47	2.20	13.73	1.96	8.20	0.76
2018 Third phase UK medium	27.80	2.57	9.13	1.95	13.07	2.06	5.60	0.63
2018 Third phase UK wet	15.80	2.44	0.93	1.93	8.47	2.55	6.40	0.70

4) The changes of plant aesthetic ratings

Plant quality was deemed respectable in the last phases of the experiment, but plant quality deteriorated during the second phase (across all irrigation treatments) (Fig 3.29). During this second phase, damage was relatively less within the wet irrigated plants ($p < 0.05$). In contrast, the wet region optimised plant quality in the first phase, but plant quality was optimised in the dry and medium region in the last phase ($p < 0.05$). From the average rating (Fig 3.30), it can be seen that plants' general ratings remained at a high level (around 4).

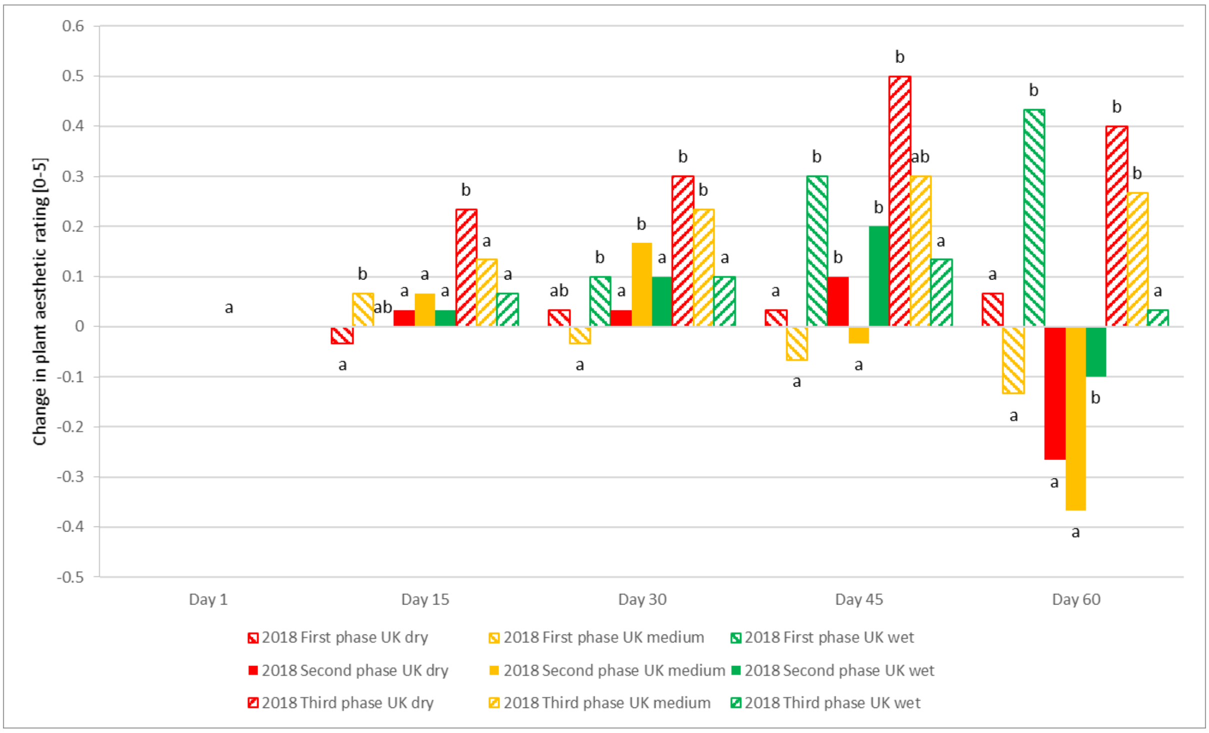

Figure 3.29 The mean change in plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

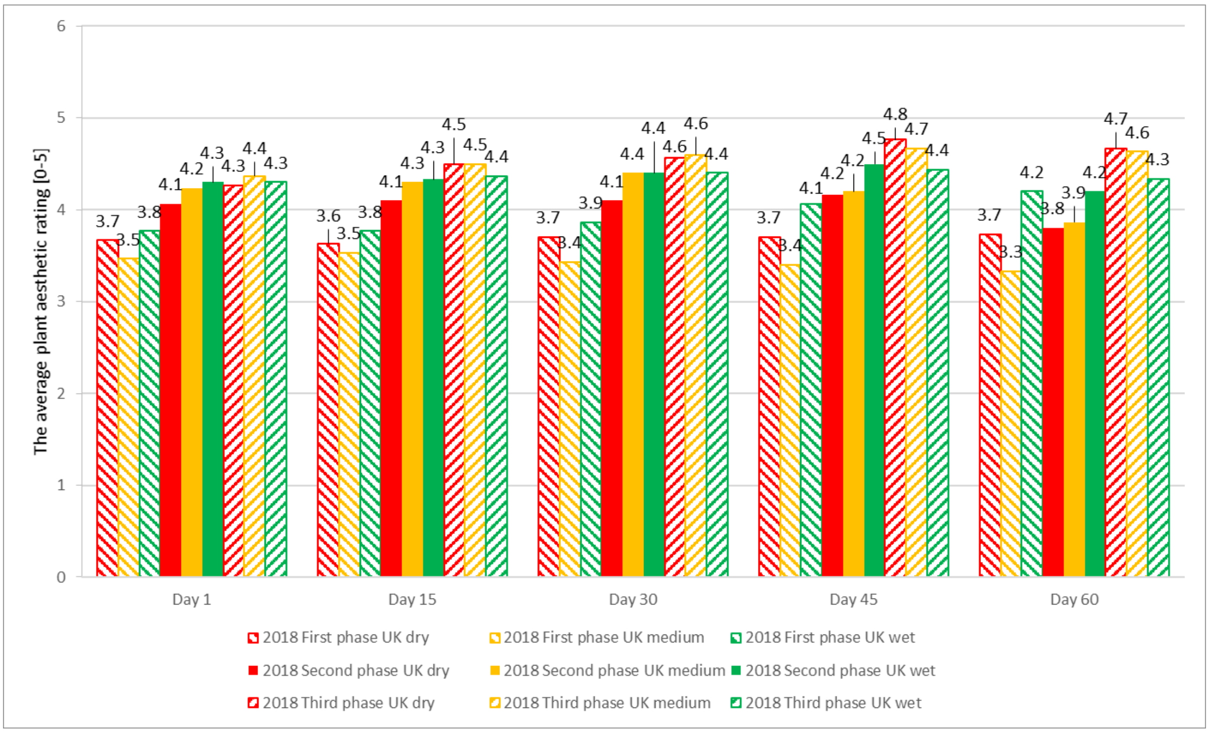

Figure 3.30 The mean value of plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

3.2.4 *Hedera* helix L.

***Hedera* – Jingmen, China**

1）The changes of plant height (extension growth)

In Jingmen, there were significant differences noted in the change of *Hedera*'s height in the first and last l phases ($p < 0.05$) (Fig 3.31). The height of plant in the third phase increased more than that in other two phases. The wet treatment in phase 1 and phase 3 significantly corresponded with good plant height by the end of experiment ($p < 0.05$). However, plant height was generally the slowest in the second phase and there was no significant effect due to the irrigation treatment ($p > 0.05$).

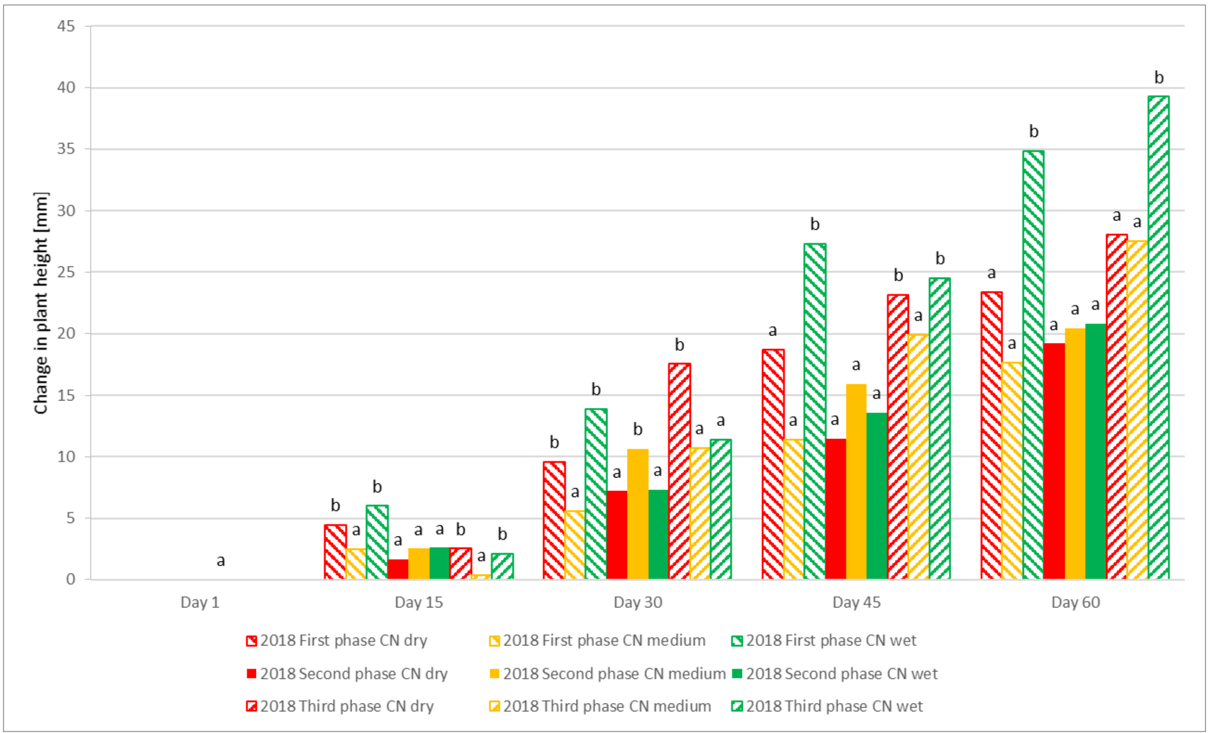

Figure 3.31 The mean change in plant height of *Hedera helix* under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread (lateral growth)

Plant spread was generally the lowest in the second phase though growth was respectable under the dry and wet treatment ($p < 0.05$) by the end of the 60 days (Fig 3.32). Spread was the greatest overall in the first phase, and it was the wet treatment that helped plant to grow much taller than others ($p < 0.05$). In contrast, in last phase, plant spread was significantly greater under the medium treatment than that under the dry and wet ($p < 0.05$).

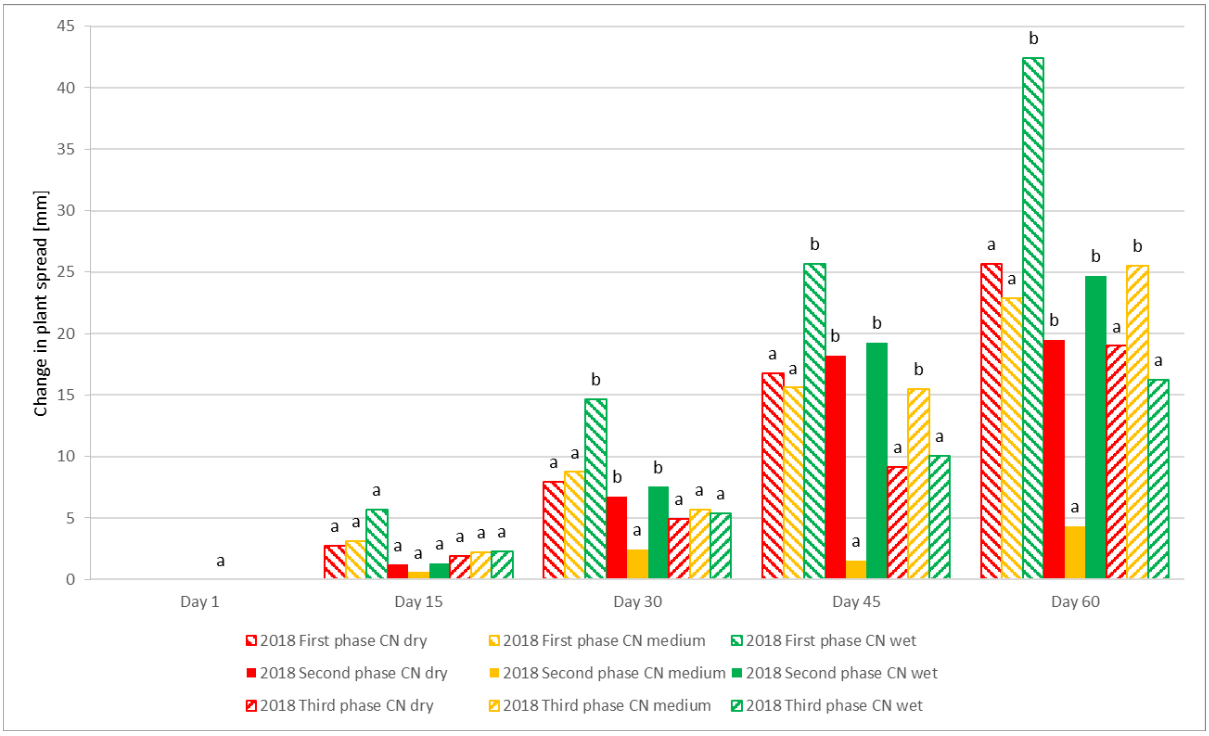

Figure 3.32 The mean change in plant spread of *Hedera helix* under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

The optimised treatment was not the same for the three different phases in the experiment (Fig 3.33). The number of leaves ($p < 0.05$), especially the number of small leaves increased significantly under the dry treatment during the first phase (6.31 per plant, Table 3.8). However, during the second phase, overall leaf number was optimal under the medium treatment ($p < 0.05$). Again, wet treatment during the last phase resulted in more leaves compared to other irrigation treatments at this time ($p < 0.05$).

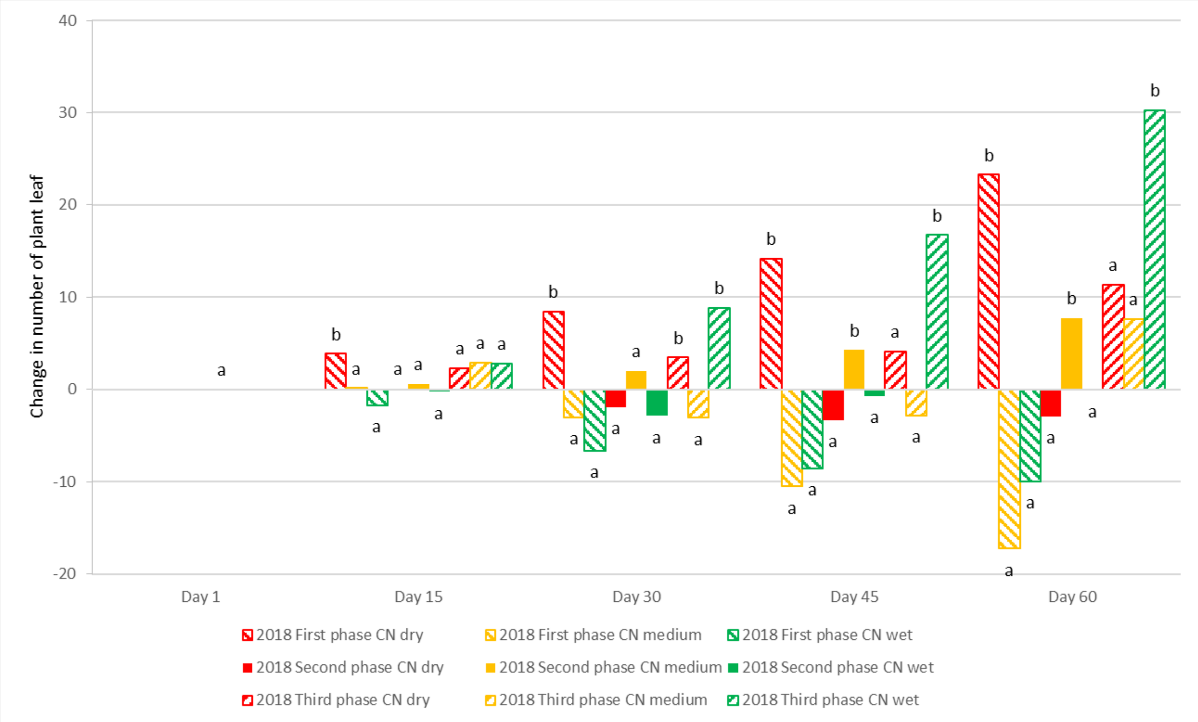

Figure 3.33 The mean change in number of plant leaves of *Hedera helix* under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.8 The mean change in numbers of different size of plant leaves of *Hedera helix* under different irrigation treatments in the Jingmen, China (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase UK dry	23.27	2.86	-0.40	2.59	11.80	1.79	11.87	2.28
2018 First Phase UK medium	-17.27	4.96	-11.47	2.72	10.67	3.09	-16.47	2.39
2018 First phase UK wet	-9.93	6.18	-13.60	2.61	22.80	3.90	-19.13	2.38
2018 Second phase UK dry	-2.93	2.38	-0.93	0.74	-1.73	2.86	-0.27	1.82
2018 Second phase UK medium	7.73	2.68	-3.93	0.83	11.60	2.46	0.07	1.87
2018 Second phase UK wet	-0.13	1.35	-4.93	1.07	8.07	1.12	-3.27	1.48
2018 Third phase UK dry	11.33	3.72	-2.73	0.86	15.33	2.86	-1.27	1.78
2018 Third phase UK medium	7.60	4.37	-3.80	1.22	20.47	5.52	-9.07	8.04
2018 Third phase UK wet	30.27	7.49	0.33	1.44	22.87	5.61	7.07	2.08

4） The changes of plant aesthetic ratings

Plant quality was deemed respectable in the first and second phases of the experiment, particularly for the wet irrigation in the first and the medium in the second phase, which were the optimal irrigation strategy in each phase ($p < 0.05$). But plant quality deteriorated during in the last phase under the dry treatment (Fig 3.34). In this phase, the medium treatment brought higher rating than other treatments ($p < 0.05$), even greater than the increase of the average rating in the second phase. From the perspective of average rating (Fig 3.35), it shows a similar trend as the aesthetic rating changes. Although the rating decreased for plants under the dry treatment in the third phase, but the actual rating remained at 4 or so, where plants were not visually different.

Figure 3.34 The mean change in plant aesthetic rating of *Hedera helix* under different irrigation treatments in Jingmen, China (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

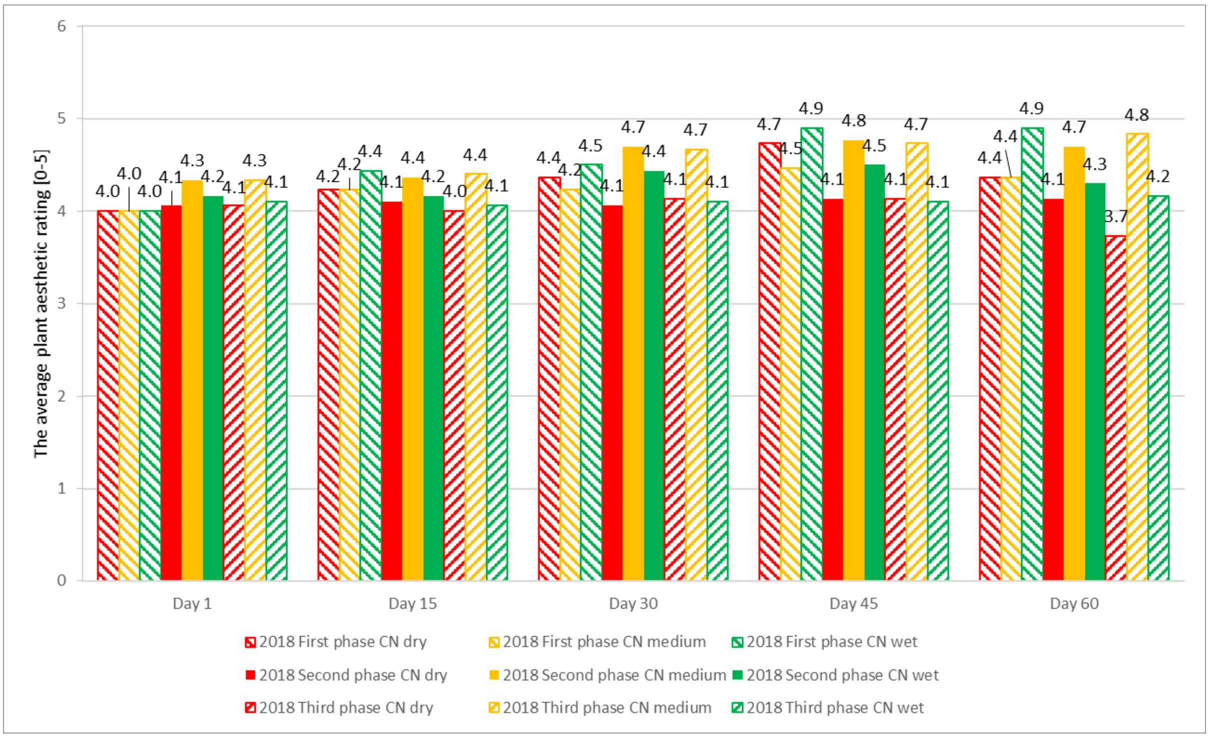

Figure 3.35 The mean value of plant aesthetic rating of *Hedera helix* under different irrigation treatments in Jingmen, China (Exp1. in 2018)

***Hedera* – Sheffield, United Kingdom**

1） The changes of plant height (extension growth)

In Sheffield, there were significant differences noted in the change of *Hedera*'s height in all phases ($p < 0.05$) (Fig 3.36).

The wet treatment in the first (and to some extent mid) phase significantly enhanced plant height ($p < 0.05$), but the wet regime was associated with slight die-back in the last phase. In the third phase, significant plant height growth is seen under both the dry and medium treatment ($p < 0.05$).

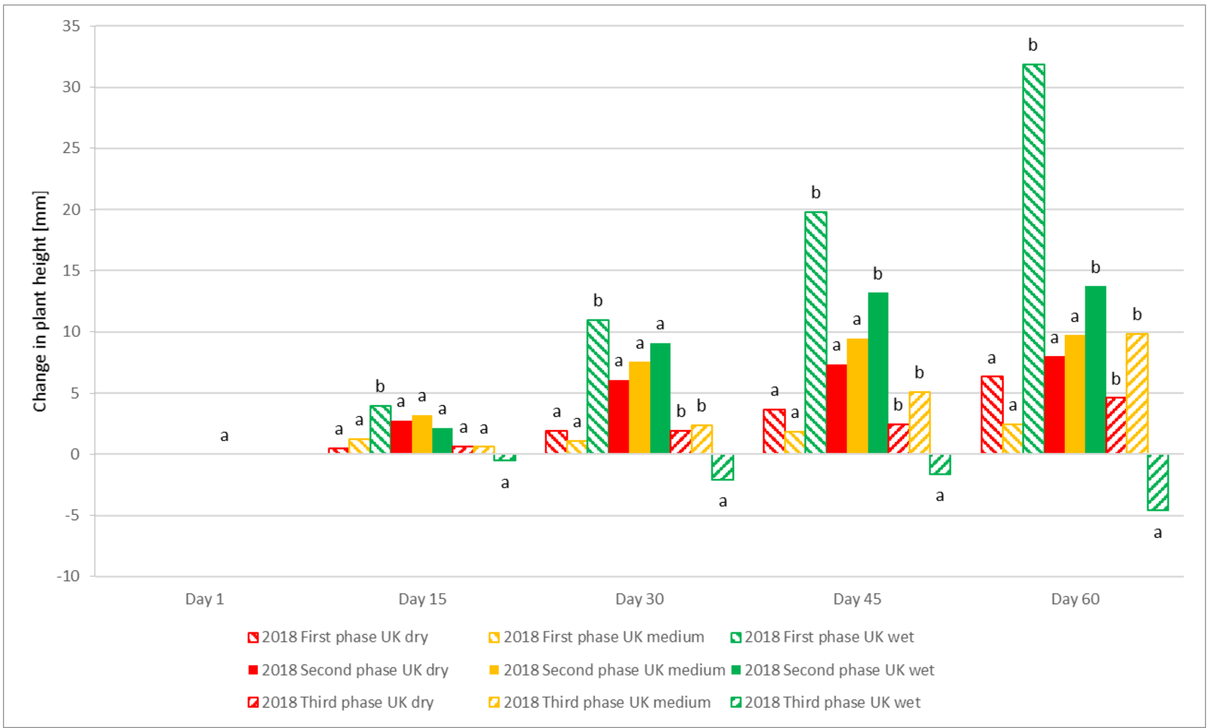

Figure 3.36 The mean change in plant height of *Hedera helix* under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

2） The changes of plant spread (lateral growth)

Plant spread was generally the shortest in last phase, although growth was respectable under the dry irrigation treatment by the end of 60 days (Fig 3.37). Both the medium and the wet irrigation treatments would lead to dieback in plants. Dieback was also evident in the dry and medium treatment during the second phase. In this phase, a significant difference was shown between the medium and the dry treatments ($p < 0.05$). Spread reaches its peak overall in the first phase, but only the spread under the dry and wet treatments is significantly longer than that under the medium treatment ($p < 0.05$).

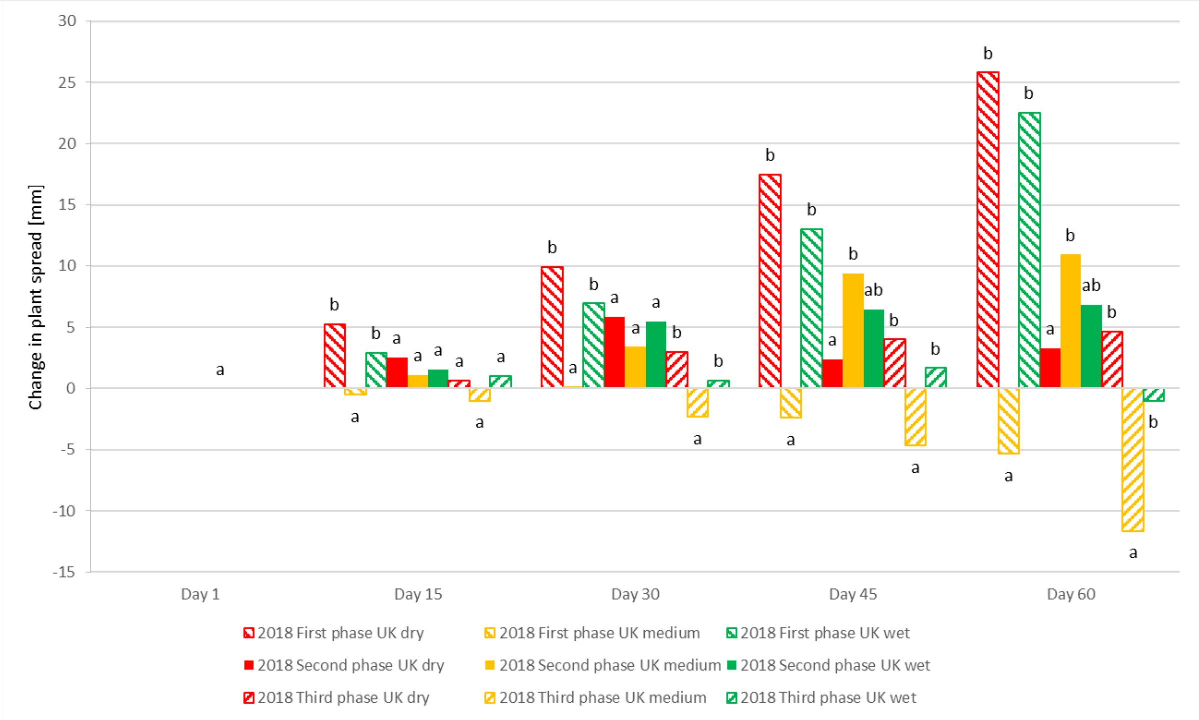

Figure 3.37 The mean change in plant spread of *Hedera helix* under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

3） The changes of numbers of plant leaves

Leaf development was the best in the third phase compared to those in other two phases (Fig 3.38). Different irrigation treatments do not bring significant difference of plant growth. Table 3.9 shows that only the medium irrigation leads to the loss of big leaves and that the numbers of leaves of all sizes will increase under other treatments. In the second phase, plant growth performance under different irrigation treatments are not significantly different from each other and the numbers of leaves of each size are close to each other as well (Table 3.9). However, the dry irrigation in the first phase results in net reduction in leaves, which is associated with the reduction in the medium size leaves (Table 3.9).

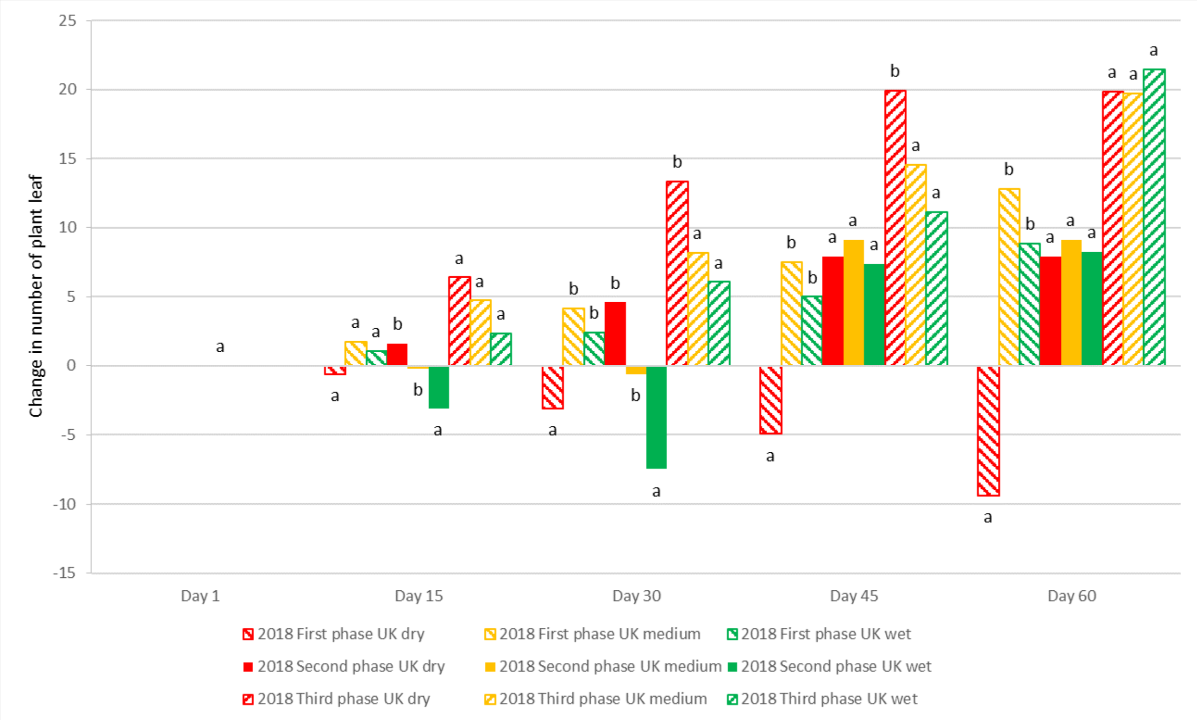

Figure 3.38 The mean change in number of plant leaves of *Hedera helix* under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

Table 3.9 The mean change in numbers of different size of plant leaves of *Hedera helix* under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2018 First phase UK dry	-9.40	4.94	11.00	1.90	-20.33	4.69	-0.07	1.19
2018 First Phase UK medium	12.80	4.65	5.67	2.98	8.67	4.37	-1.53	0.41
2018 First phase UK wet	8.87	4.23	2.93	1.28	6.67	4.00	-0.73	0.30
2018 Second phase UK dry	7.93	2.24	-3.27	1.29	11.27	2.72	-0.07	0.33
2018 Second phase UK medium	9.13	3.42	-2.67	0.93	12.00	3.33	-0.20	0.20
2018 Second phase UK wet	8.27	2.00	-1.80	0.50	9.93	1.95	0.27	0.27
2018 Third phase UK dry	19.87	1.42	1.67	0.83	11.87	0.34	6.33	0.91
2018 Third phase UK medium	19.73	1.21	-0.93	0.63	12.33	0.45	8.33	0.94
2018 Third phase UK wet	21.47	0.98	0.73	0.13	12.73	0.42	8.00	0.92

4） The changes of plant aesthetic ratings

Plant quality was deemed respectable across all phases after 60 days, and no negative score was seen in all the phases of the experiments. The wetter condition seems optimal in the first and second phases, but less so in the third phase (Fig 3.39). It should be noted that plant quality dropped in the second phase after 30 days, but rebounded after that. From Fig 3.40, it can be seen that the actual aesthetic rating of the second phase is not significantly different, although the rating growth of the second phase is a little lower than that of the other two phases.

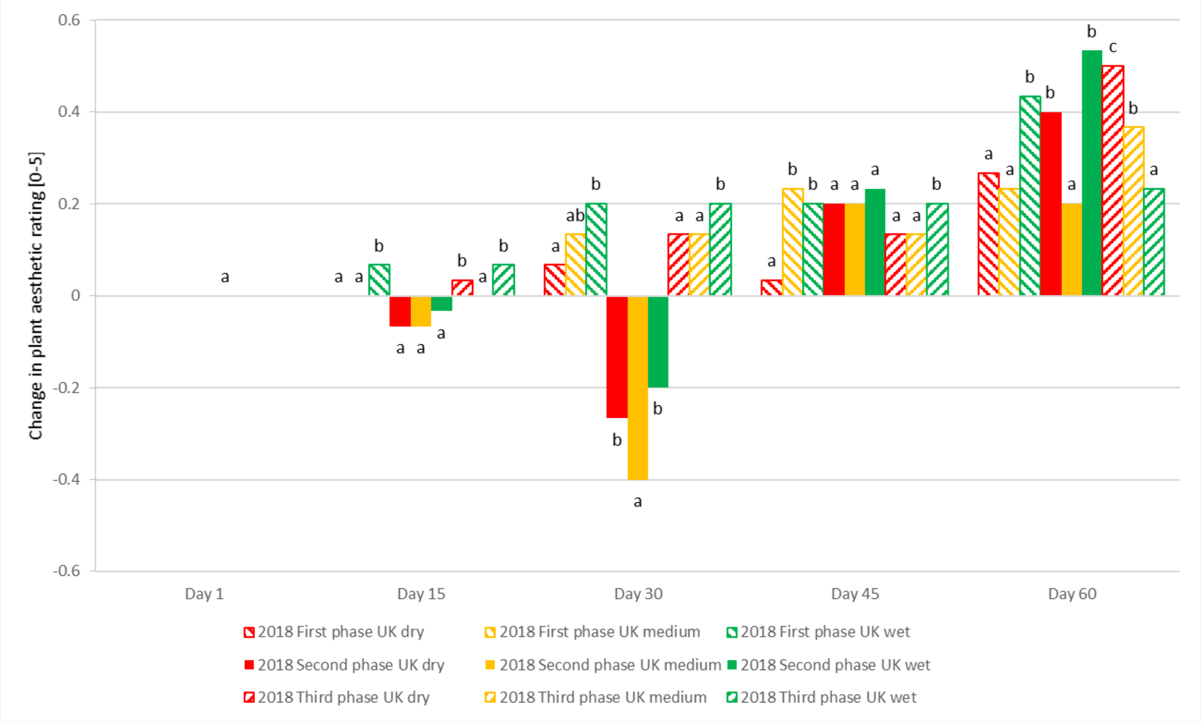

Figure 3.39 The mean change in plant aesthetic rating of *Hedera helix* under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018) (NB. The letters on the graph denote difference from the transformed values)

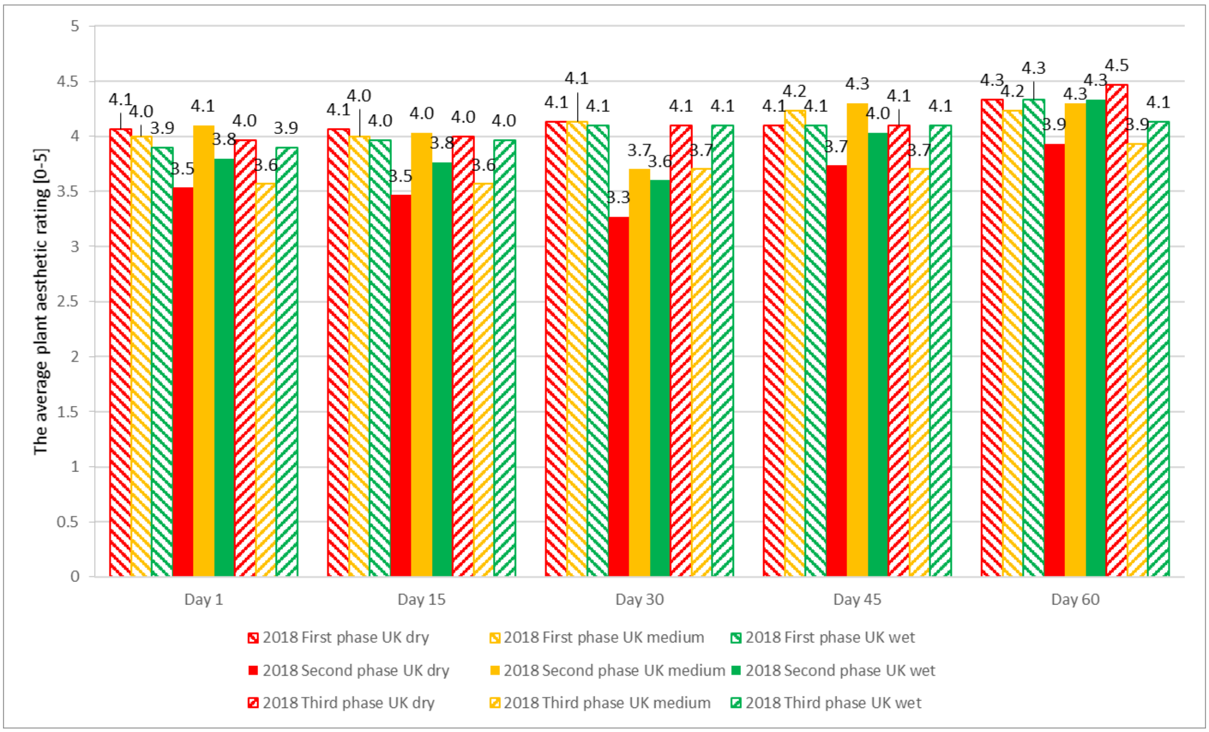

Figure 3.40 The mean value of plant aesthetic rating of *Hedera helix* under different irrigation treatments in Sheffield, United Kingdom (Exp1. in 2018)

3.2.5 Correlations between Meteorological Factors and Plant Growth

3.2.5.1 Change in meteorological factors

The average daily air temperature at 2 metres above the ground Jingmen and Sheffield is shown in Fig 3.41. The data start from May 1st to October 30th 2018. It can be seen that Jingmen is generally above Sheffield during the whole experiment in 2018. The gap between their average daily air temperatures is about 10 °C. The temperature changes in these two cities, however, show a similar trend. The average daily temperature reached the peak in phase 2 for both locations, with China being nearly 32 °C on 21 July and UK 23.4 °C on 23 July. The average daily temperature in phase 1, for both countries, comes between that in phase 2 and phase 3. In phase 3, both cities experienced the lower range of average daily temperatures, compared to other two phases, with the minimum of 12.8 °C on October 21st in Jingmen and 2.4 °C on October 29th in Sheffield.

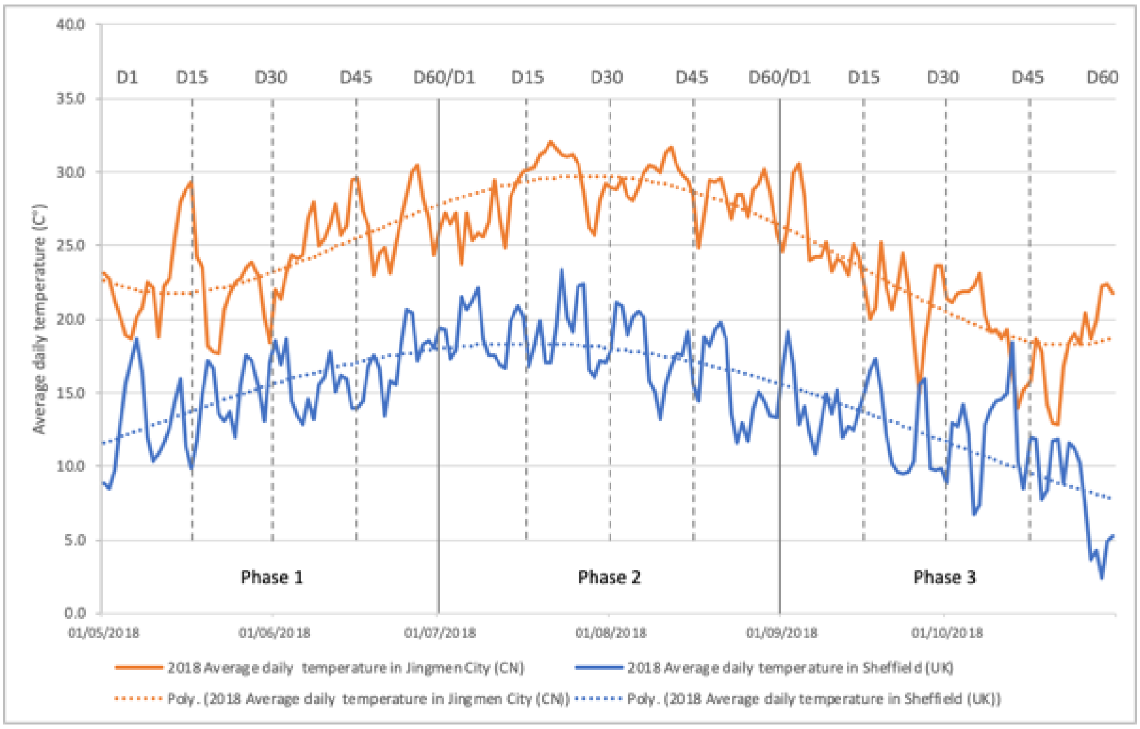

Figure 3.41 The average daily air temperature at 2 metres above the ground in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp1. in 2018)

Unlike the air temperature, the changes in average daily humidity, for both countries, are not that drastic (Fig 3.42). Generally, Sheffield had a higher relative humidity than Jingmen. In addition, the average daily humidity in Sheffield was relatively stable with little difference among three phases compared with Jingmen. Sheffield's average daily humidity remained above 90%. However, the average daily humidity in Jiangmen experienced big waves with the biggest fluctuation in phase 3 reaching a maximum of 99% on 26th September and a minimum of 24% on 30th October in 2018.

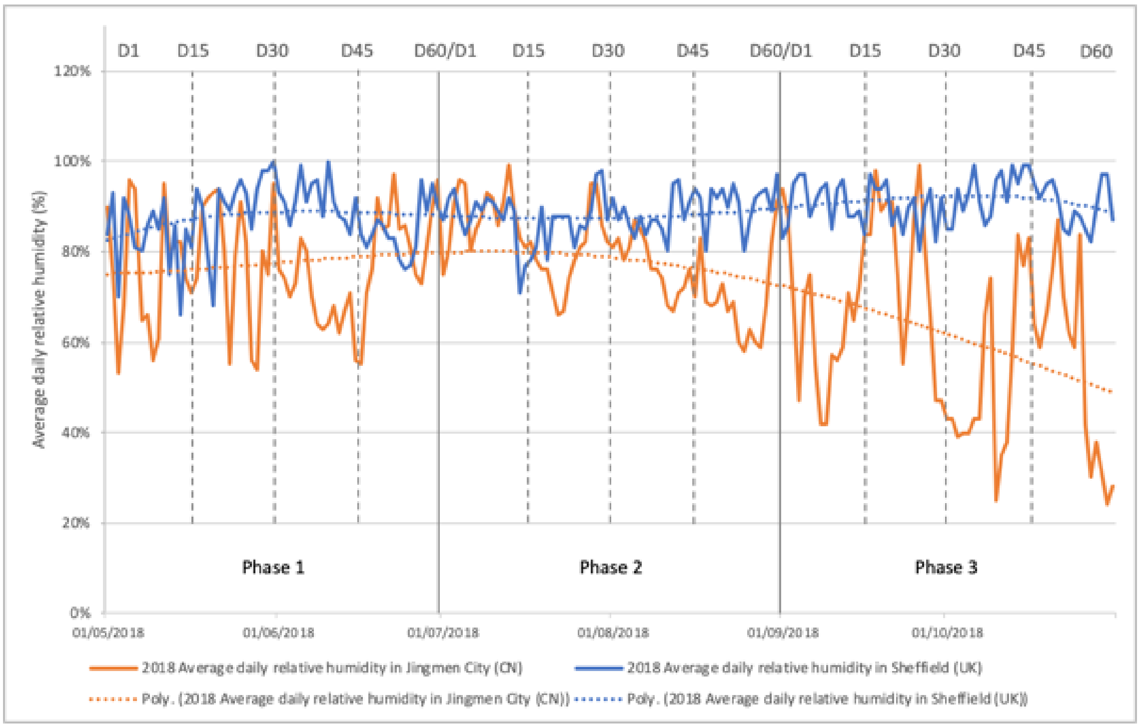

Figure 3.42 The average daily relative humidity at 2 metres above the ground in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp1. in 2018)

Fig 3.43 shows that the precipitation through the whole experiment is irregular and instable in terms of frequency and amount. Generally, the total average daily precipitation in Jingmen is slightly greater than that in Sheffield. For Jiangmen, phase 2 has the generally higher rainfall frequency and amount, but the biggest amount of precipitation is seen in phase 1 reaching 65.1 mm on June 30th. While for Sheffield, phase 3 has the most frequent rainfall, the biggest amount of which comes at 62.6mm on September 20th.

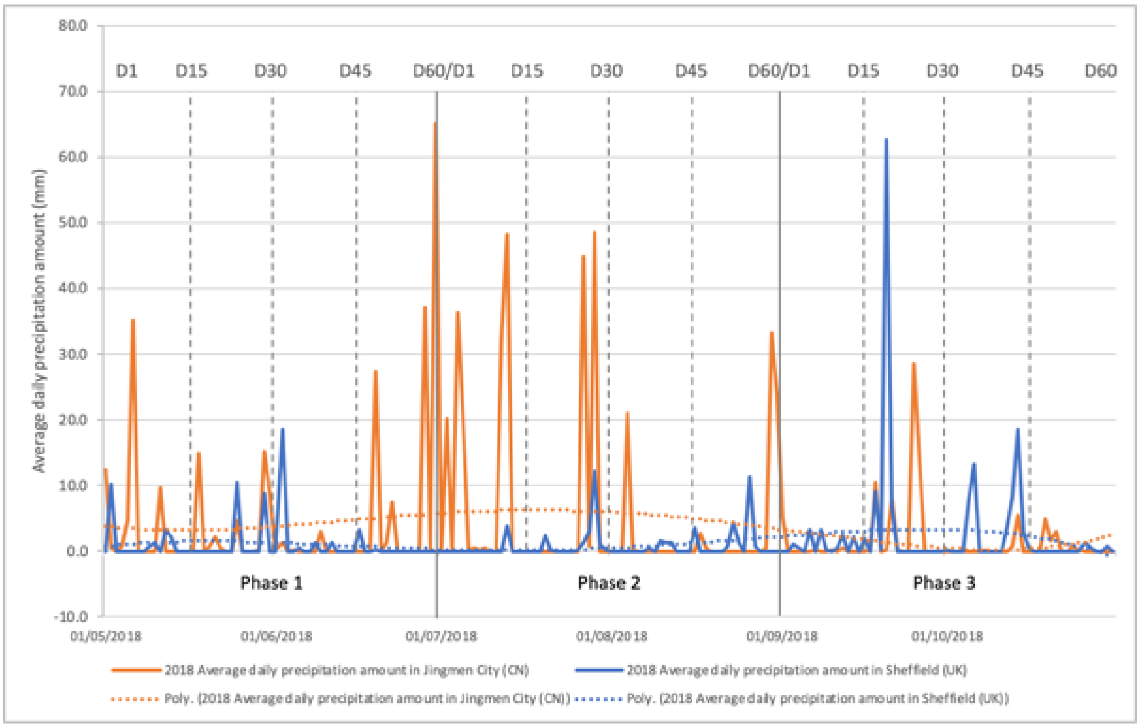

Figure 3.43 The average daily precipitation amount in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp1. in 2018)

The average daily pressure curves are different from the other meteorological factors (Fig 3.44). It can be seen that Sheffield's average daily pressure is generally above Jingmen's. For Sheffield, the pressure maintained at the level of around 1020 hPa throughout all three phases. It rose to the peak of 1033.2 hPa on 25th September in phase 3, while it reached the minimum of 998.0 hPa on 2nd May in Phase 1. For Jiangmen, the pressure curve is at the lowest part in phase 2 while increase to the highest one in phase 3. However, in each phase, the pressure change is relatively flat. The maximum average daily pressure of 1001.7 hPa occurred on 27th October, while the minimum one was 974.4 hPa on 4th July.

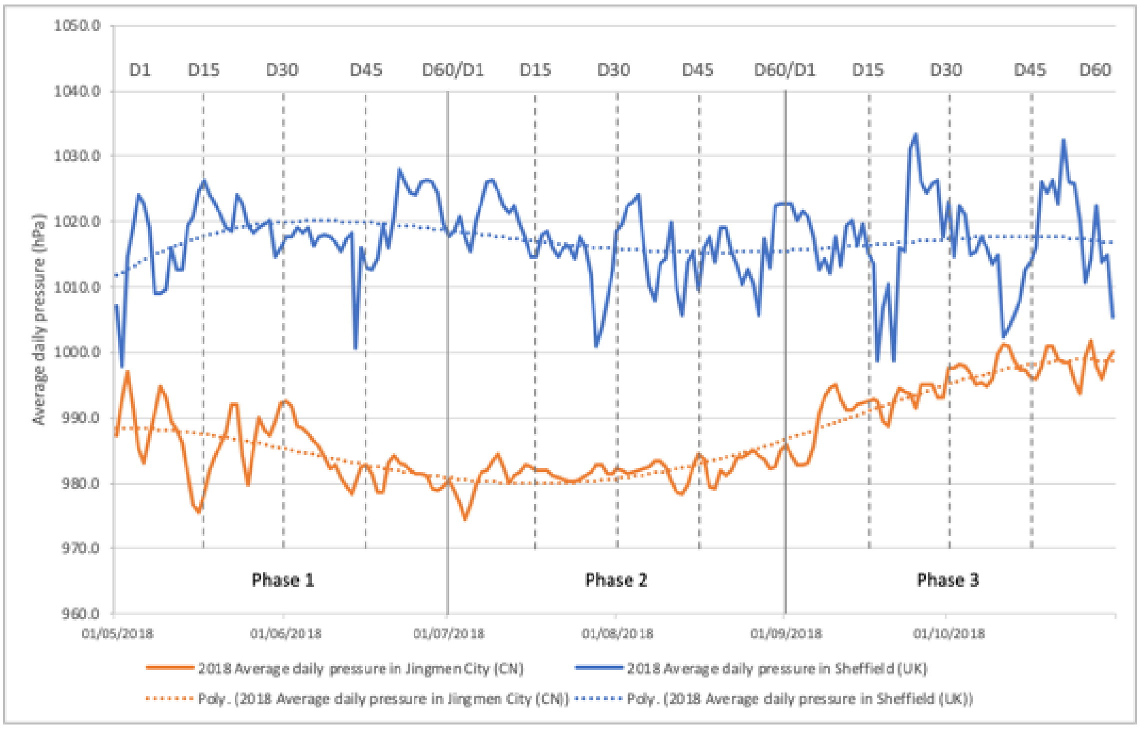

Figure 3.44 The average daily pressure in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp1. in 2018)

3.2.5.2 *Vinca major* 'Variegata'

Table 3.10 shows a general strong linear correlation (r = -0.41 to -0.75) between relative humidity and plant growth, which means that relative humidity is a key factor for plant growth. It is the plant height that has the strongest relationship with relative humidity under all the three treatments, namely dry treatment (r = -0.743), medium treatment (r = -0.751) and wet treatment (r = -0.747). For plant spread, however, its relationship with relative humidity in the wet treatment is relatively weak (r = -0.413). Except for humidity, the relationships between other meteorological factors and plant growth are generally very weak ($|r| \leq 0.20$). And these relationships are not always similar. Air temperature and pressure have positive correlation with plant growth while precipitation has a negative one with plant growth.

Table 3.10 The correlation analysis between meteorological factors and *Vinca major* 'Variegata' growth (Exp1. in 2018)

IRRIGATION TREATMENT	PLANT INDEX	TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]
Dry	Plant height	0.050	-0.743**	-0.193	0.106
	Plant spread	-0.203	-0.542**	-0.180	0.101
	Plant leaves	0.065	-0.618**	-0.163	0.113
Medium	Plant height	0.026	-0.751**	-0.204	-0.141
	Plant spread	0.264	-0.669**	-0.196	-0.239
	Plant leaves	0.155	-0.665**	-0.174	-0.241
Wet	Plant height	0.035	-0.747**	-0.172	-0.167
	Plant spread	0.067	-0.413*	-0.039	-0.144
	Plant leaves	0.031	-0.690**	-0.053	-0.261

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

3.2.5.3 *Hosta* 'Blue Mouse Ears'

Table 3.11 shows that *Hosta's* growth and the meteorological factors mainly have weak or very weak linear relationships ($|r| \leq 0.40$). Exceptions are the stronger correlation between plant leaves with the temperature (r = 0.555) and pressure (r = -0.588) under the medium treatment. Generally, air temperature has a little more impact on plant growth than other meteorological factors. In addition, only air pressure shows a negative relationship with plant growth. The rest three factors, relative humidity, pressure, and precipitation amount, are all positively correlated with plant growth.

Table 3.11 The correlation analysis between meteorological factors and *Hosta* 'Blue Mouse Ears' growth (Exp1. in 2018)

IRRIGATION TREATMENT	PLANT INDEX	TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]
Dry	Plant height	0.510*	0.121	0.287	-0.346
	Plant spread	0.405*	0.021	0.170	-0.229
	Plant leaves	0.184	0.316	0.223	-0.195
Medium	Plant height	0.333	0.178	0.206	-0.212
	Plant spread	0.336	-0.062	0.137	-0.211
	Plant leaves	0.555**	0.100	0.451*	-0.588**
Wet	Plant height	0.025	0.167	0.081	0.011
	Plant spread	0.488*	-0.015	0.216	-0.304
	Plant leaves	0.361	0.399	0.274	-0.184

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

3.2.5.4 *Heuchera* 'Marmalade'

It is indicated in Table 3.12 that mainly weak or very weak linear relationships ($|r| \leq 0.40$) exist between *Heuchera*'s growth and meteorological factors. Only three relationships are stronger: negative correlations between plant height and humidity (r = -0.642) and pressure (r = -0.552) respectively and a positive correlation between plant height and temperature (r = 0.551), all under the wet treatment. Also, no strong negative or positive correlations are found between meteorological factors and plant growth.

Table 3.12 The correlation analysis between meteorological factors and *Heuchera* 'Marmalade' growth (Exp1. in 2018)

IRRIGATION TREATMENT	PLANT INDEX	TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]
Dry	Plant height	0.438*	-0.318	-0.062	-0.256
	Plant spread	0.007	-0.171	-0.007	-0.034
	Plant leaves	-0.360	0.188	-0.231	0.339
Medium	Plant height	0.270	-0.151	0.117	-0.214
	Plant spread	-0.372	0.133	-0.299	0.436*
	Plant leaves	-0.351	0.356	-0.213	0.388
Wet	Plant height	0.551**	-0.642**	0.070	-0.552**
	Plant spread	-0.132	-0.210	-0.089	0.021
	Plant leaves	-0.166	0.190	-0.135	0.209

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

3.2.5.5 *Hedera helix* L.

The correlations between *Hedera*'s growth and environment changes generally show positivity for temperature and rainfall, but negativity in terms of relative humidity and pressure (Table 3.13). Among them, the relative humidity has the strongest correlation with plant growth compared to other meteorological factors. Plant leaf has relatively stronger positive correlation with pressure in the medium treatment (r = 0.574). Another relatively stronger correlation is found between plant height and relative humidity, but it is negative (r = -0.722).

Table 3.13 The correlation analysis between meteorological factors and *Hedera helix* growth (Exp1. in 2018)

IRRIGATION TREATMENT	PLANT INDEX	TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]
Dry	Plant height	0.409*	-0.722**	0.049	-0.505*
	Plant spread	0.310	-0.291	0.006	-0.247
	Plant leaves	-0.260	0.052	0.171	-0.007
Medium	Plant height	0.357	-0.636**	0.019	-0.436*
	Plant spread	0.397	-0.609**	0.100	-0.458*

	Plant leaves	-0.575**	0.332	-0.365	0.574**
Wet	Plant height	0.322	-0.519**	-0.057	-0.285
	Plant spread	0.503*	-0.321	0.186	-0.466*
	Plant leaves	-0.518**	-0.232	-0.346	0.356

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

3.2.5.6 The correlation between plant aesthetic rating and all other factors

Despite that aesthetic ratings of different plant species have different correlations with meteorological factors, the relationships are generally weak or very weak ($|r| \leq 0.40$) (Table 3.14). However, air temperature and pressure are shown to have stronger correlations with aesthetic rating than other factors. In terms of plant species, *Hosta's* rating has the strongest correlation with meteorological factors, while *Heuchera* and *Hedera's* have the weakest relationships with meteorological factors. Not all meteorological factors are shown to have similar correlations with plant aesthetic rating. For *Vinca*, its aesthetic rating is negatively correlated with air temperature and precipitation amount, while is positively correlated with relative humidity and pressure. However, in contrast, for other plant species, relative humidity and pressure have only negative correlation with their ratings.

On plant growth index, plant's aesthetic rating is mainly related to change in plant height and plant leaf number, showing positive correlations, particularly in the wet treatment.

Table 3.14 The correlation analysis between plant growth and plant aesthetic rating and between meteorological factors and plant aesthetic rating (Exp1. in 2018)

		TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]	Plant Height	Plant Spread	Plant leaves
Plant aesthetic rating - *Vinca*	Dry	-0.288*	0.022	-0.106	0.142	0.117	0.324*	0.339*
	Medium	-0.485**	0.122	-0.272	0.375*	0.166	0.066	0.089
	Wet	-0.230	-0.015	-0.099	0.143	0.303*	0.388**	0.410**
Plant aesthetic rating - *Hosta*	Dry	0.234	-0.106	0.051	-0.169	0.608**	0.711**	0.492**
	Medium	0.542**	-0.598**	0.161	-0.418**	0.176	0.128	0.140
	Wet	0.489**	-0.256	0.178	-0.393**	0.164	0.461**	0.243
Plant aesthetic rating - *Heuchera*	Dry	0.074	-0.242	0.082	-0.178	-0.097	0.071	0.290
	Medium	0.178	-0.349*	0.185	-0.348*	-0.052	-0.022	-0.019
	Wet	0.015	-0.180	-0.110	-0.051	0.410**	0.606**	0.341*
Plant aesthetic rating - *Hedera*	Dry	-0.064	0.082	-0.004	0.004	0.202	0.094	0.255
	Medium	0.281	-0.397**	0.026	-0.273	0.581**	0.281	-0.004
	Wet	0.045	0.019	0.097	-0.090	0.254	0.351*	-0.119

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

3.2.6 Results Overview for Exp 1

When species are compared across common scales for each parameters and across both countries, it is evident that *Vinca* is a species that grows well, especially in the latter part of summer in China, with relatively high values for increases in height (Fig 3.45), spread (Fig 3.46) and leaf number (Fig 3.47). In terms of height, *Vinca* has an average increase of 71 mm, whereas in other species it is only 10 mm. Despite this, aesthetic ratings dropped in China plants, but only in the middle of summer (Fig 3.48). There was some evidence that *Vinca* responded better to wetter regimes in early and late summer in China at least in terms of extension growth, although the same effect was not observed in the UK. *Hedera* was another species that performed well in China, although again growth was more subdued in mid-summer, and at other phases wetter regimes again were more favourable (Figs 3.45 and 3.46), although leaf retention and aesthetic quality did not match the growth data (Figs 3.47 and 3.48). Although growth was not spectacular in *Hedera* in the UK, it was generally better than equivalent performances from *Hosta* and *Heuchera*. *Hosta*, by and large, struggled in both mid and late phases in both China and UK (Figs 3.45 to 3.48). The performance of *Heuchera* in terms of growth, did not match that of *Vinca* nor *Hedera* and shoot extension was relatively small and often consistent across treatments. Shoot spread, however, was respectable (this is a species that tends to spread more than actually grow upwards), although again there was some suggestion that conditions in mid-summer in China impacted on lateral growth (Figs 3.46 to 3.48).

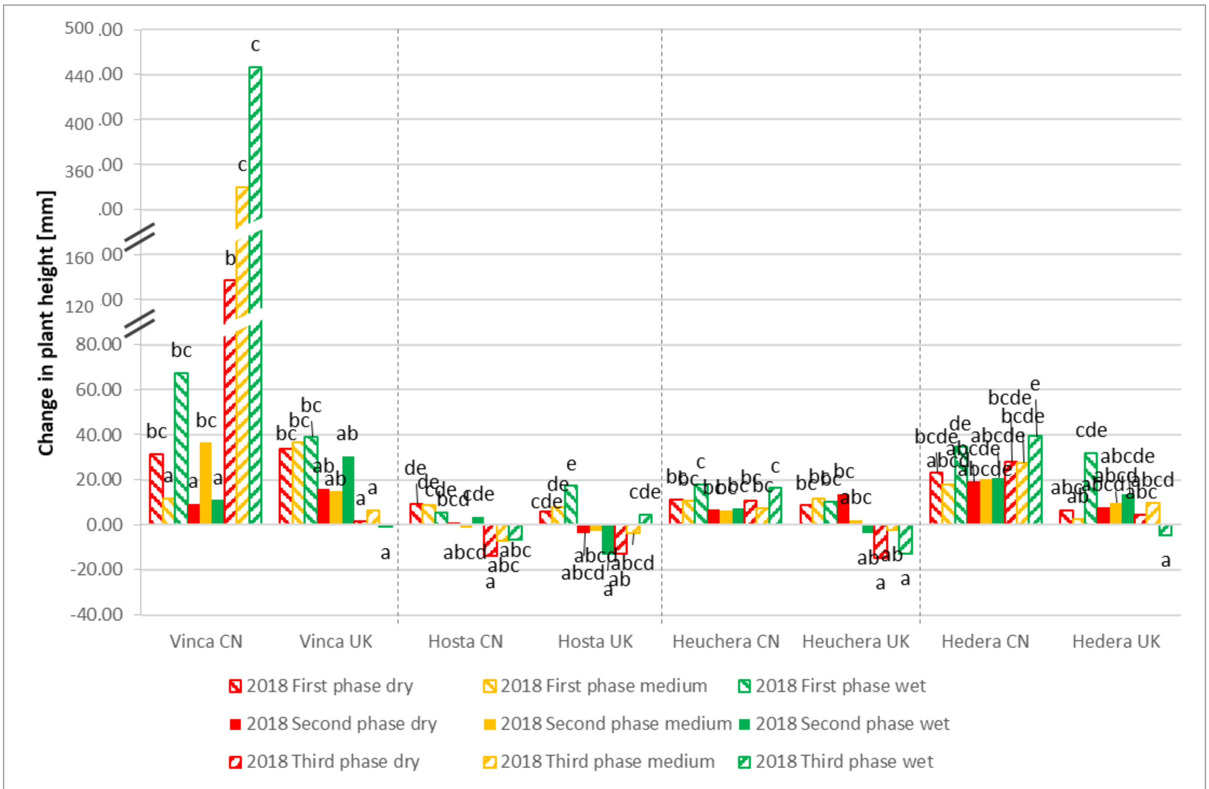

Figure 3.45 The mean change in plant height in Day 60 (four plant species in two cities during 3 phases) (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

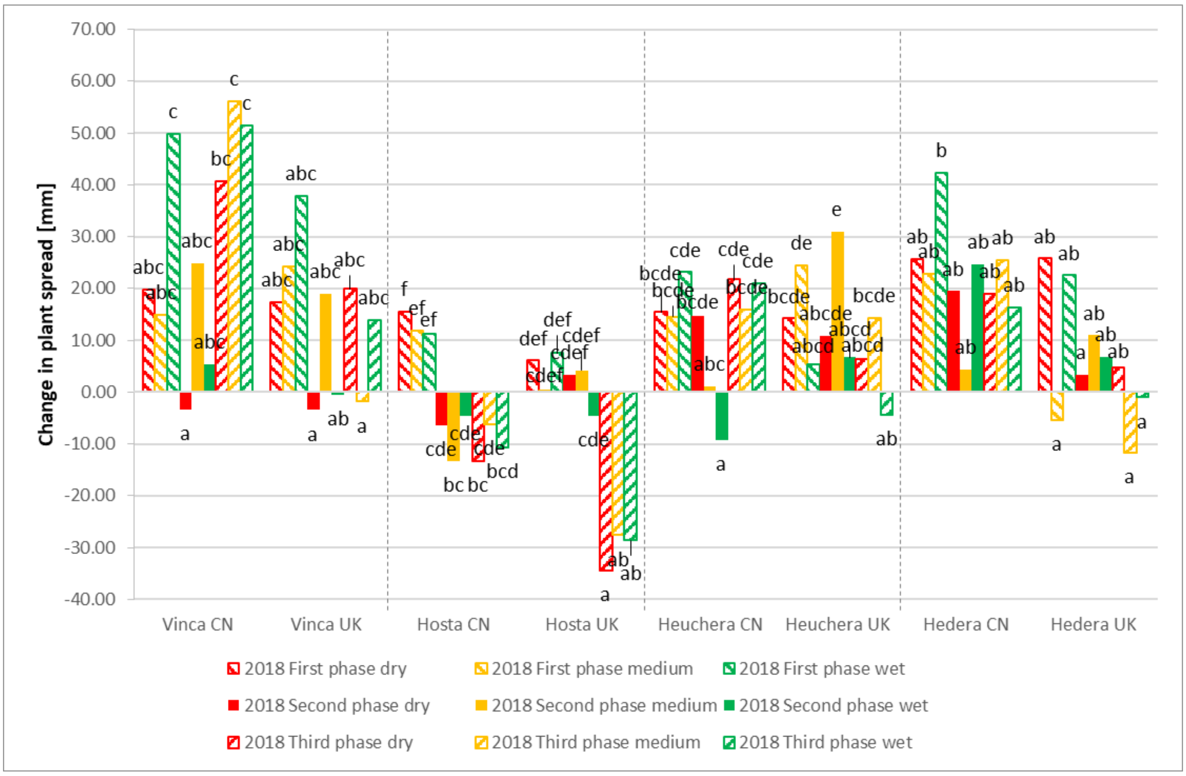

Figure 3.46 The mean change in plant spread in Day 60 (four plant species in two cities during 3 phases) (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

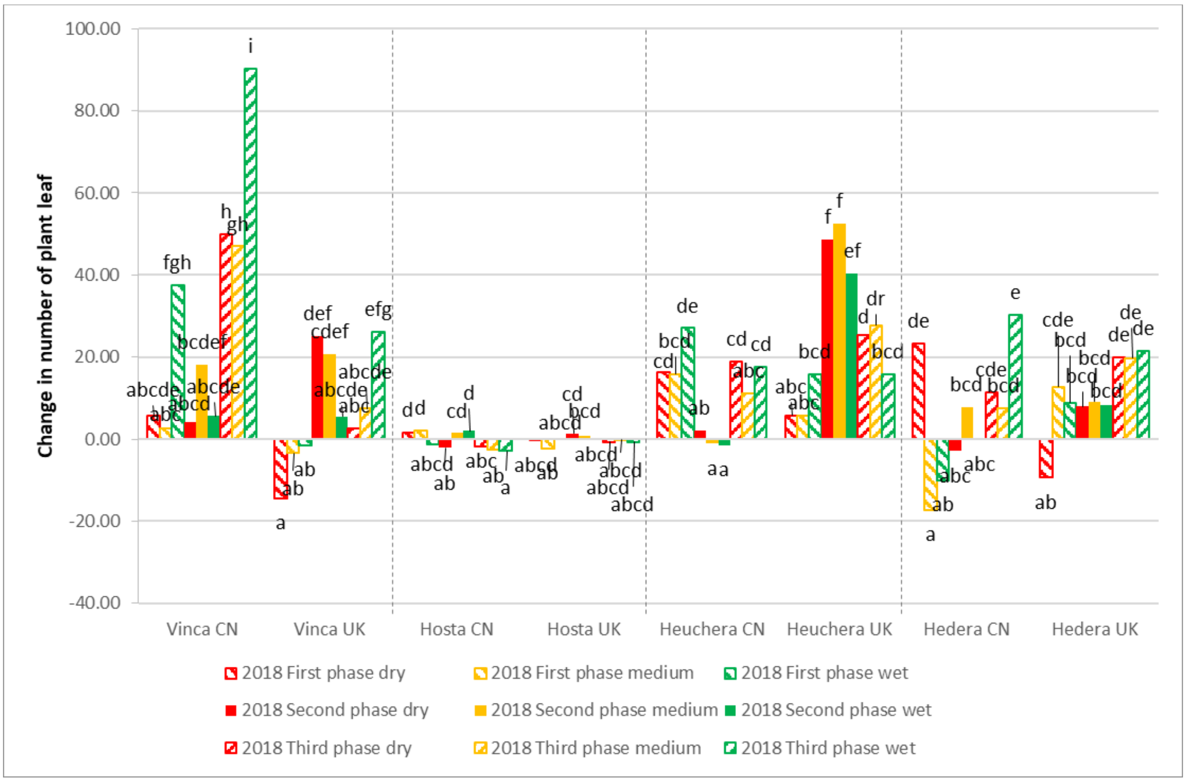

Figure 3.47 The mean change in plant leaf number in Day 60 (four plant species in two cities during 3 phases) (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

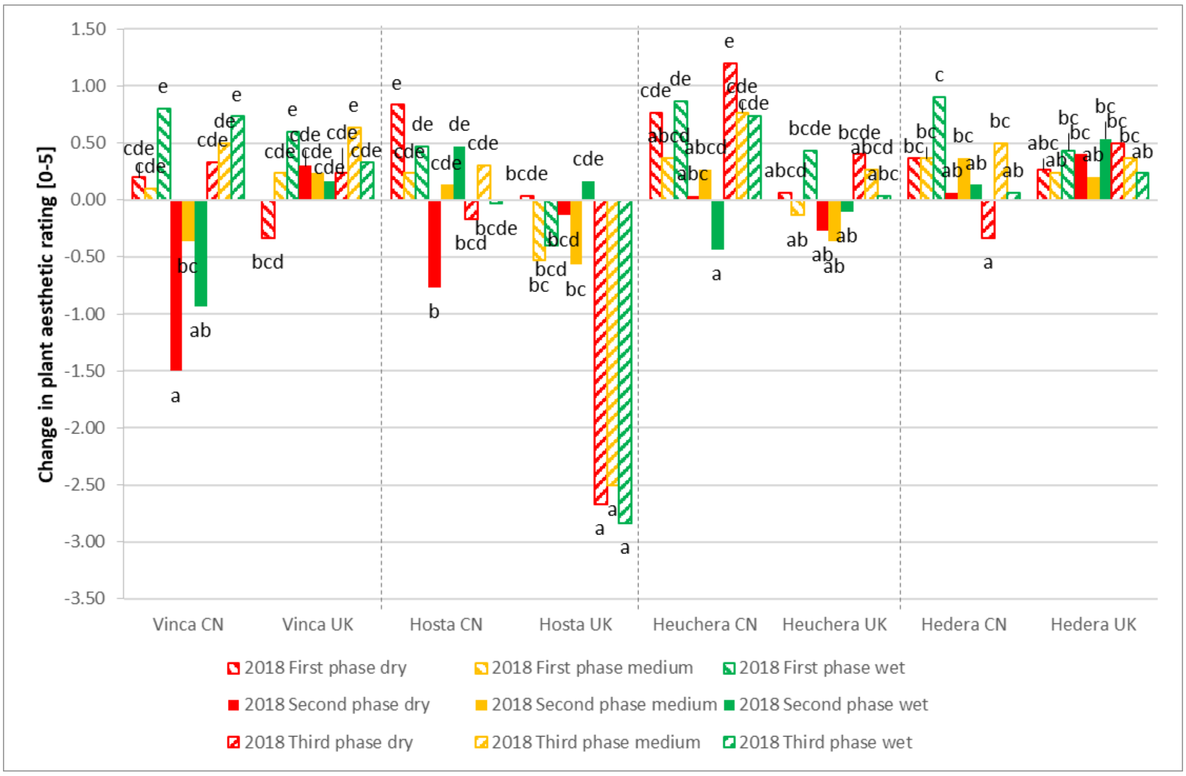

Figure 3.48 The mean change in plant aesthetic rating in Day 60 (four plant species in two cities during 3 phases) (Exp1. in 2018) (NB. the letters on the graph denote difference from the transformed values)

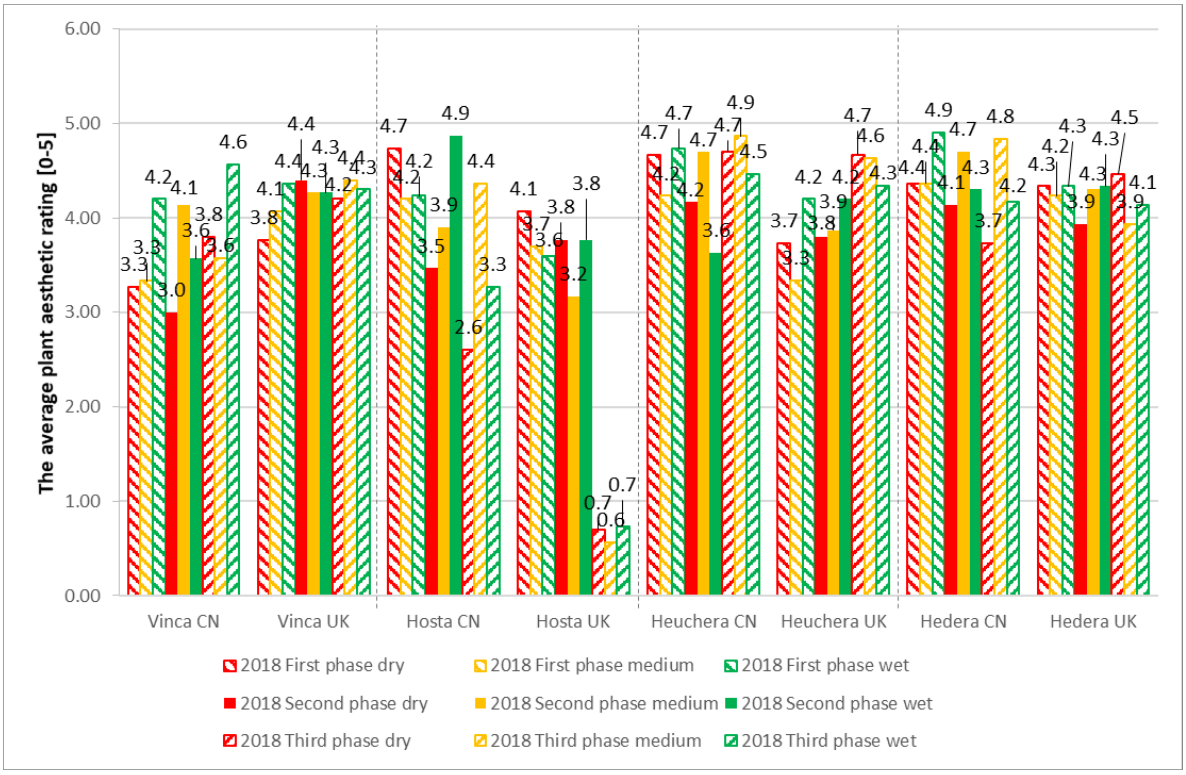

Figure 3.49 The mean value of plant aesthetic rating in Day 60 (four plant species in two cities during 3 phases) (Exp1. in 2018)

3.3 EXPERIMENT DISCUSSION

3.3.1 Overall Discussion

Of the four species tested, growth was most notable in *Vinca*, and, to a more moderate extent, *Hedera*. Location, time, and irrigation treatment were all important factors. Growth in both *Vinca* and *Hedera* was much more noticeable in China than that in the UK. Growth in China was also optimised in the third phase by applying more water (Wet treatment). In contrast, growth was better in the UK in the first phase; and in the case of *Hedera,* better growth was ensured by the wet irrigation treatment. Growth in *Vinca* tended to be shown in the extension of leading shoots (i.e., plant height) whereas in *Hedera* it was both height and width. For the two species, which were more drought sensitive (i.e., *Hosta* and *Heuchera*), growth was greater in the second phase compared to that in the third phase. The loss of quality and leaf die-back in the third phase in the UK may relate to natural die-back of leaves due to the onset of autumn, lower temperatures and light levels. *Hosta,* for example, appeared to enter a natural dormancy with dieback and shrinkage common in the third phase of the experiment both in UK and China.

With the exception of *Vinca*, growth was very limited – extensive growth usually being less than 4 cm. This can be interpreted as both a negative and positive factor. For the negative perspective, it implies that, in a lot of situations, growth was sub-optimal and was held back by one or more factors (i.e., limited size of growing media, wind). For example, the relatively limited size of growing media leads to the limited soil capacity of the LWS, which further results in less heat absorption capacity and inhibited root growth. The root development of plant growing in the LWS could be strongly affected by the sharper temperature change of the growing media than that of the ground soil. Specifically, the temperature of LWS is higher in the summer and lower in the winter than the temperature of the ground soil. However, if such plants can be considered healthy, judging from the leaf number and health, this could be a positive factor in that in many green walls, the objective is not to have excessive shoot growth but rather the plants remain compact without the need for frequent trimming.

In terms of the number of plant leaves, plants with high drought tolerance capacity gains a gradual increase in plant leaf number as the experiment went on, while plants with moderate drought tolerance hardly experiences this significant change of leaf number from the statistical and visual perspective. Although the plants with low drought tolerance become statistically different in some phases, differences are not observable generally.

3.3.2 Plant Species

3.3.2.1 *Vinca major* 'Variegata'

For *Vinca*: 1) The difference of plant growth is generally greater in Jingmen than that in Sheffield. It could be noticed in each phase that the growth differences in both plant size and leaf number are greater in Jingmen than that in Sheffield (Figs 3.45 to 3.47). In the visual aspect, *Vinca* growing in Jingmen has relatively long and rapidly growing stems, which dramatically increase the size of the plant. Although the *Vinca* has relatively lower growth rate in Sheffield, both new and old stems are growing, which makes the plant visually denser than that in Jingmen and potentially benefit the aesthetics rating.

2) The trend of plant growth over time shows difference between Jingmen and Sheffield. In Jingmen, the greatest increase in plant growth occurs in the third phase; while the smallest changes of plant size and leaf number appear in the second phase. In Sheffield, however, the peaks of plant size increase and leaf number growth do not come in the same time, and no uniform trend could be found. This phenomenon may suggest that the growth of *Vinca* is dramatically affected by certain climatic factor within a specific range. However, lower soil moisture content could inhibit plant growth in terms of plant size and leaf number.

3) The optimal irrigation treatment for plant growth varies with different phases and environments (cities). In Jingmen, the medium and the wet treatments are the generally ideal irrigation for *Vinca's* growth. It is the wet treatment in the first and third phases that significantly enhance the plant growth; while the optimal treatment becomes the medium for the second phase. This may be caused by high frequency of irrigation especially in the day-time to rise up the soil moisture into the threshold value of Wet Irrigation Treatment, which could potentially do harm to plants in the second phase. In Sheffield, the best irrigation treatment is the wet in the first and the third phases while no specific optimal treatment for the second phase. Different plant indexes respond differently to different treatments in the second phase. For instance, the optimal treatment for plant height, plant spread and plant leaf numbers are the wet, the medium and the dry treatment respectively (Figs 3.45 to 3.47). In summary, except for the relatively harsh environment in the second phase, more wet soil moisture could promote *Vinca's* growth (Table 3.15). In addition, the dry and the wet treatments cause significant difference in most cases in both cities, while the medium treatment has no uniform tendency shown.

Table 3.15 The optimal and economic irrigation treatment for *Vinca major* 'Variegata' in single species plant scheme in LWS in different cities (Exp1. in 2018)

TIME	JINGMEN (OPTIMAL)	JINGMEN (ECONOMIC)	SHEFFIELD (OPTIMAL)	SHEFFIELD (ECONOMIC)
Phase 1	Wet treatment	Wet treatment	Wet treatment	Medium treatment
Phase 2	Medium treatment	Medium treatment	Medium treatment	Wet treatment
Phase 3	Wet treatment	Wet treatment	Wet treatment	Medium treatment

3.3.2.2 *Hosta* 'Blue Mouse Ears'

For *Hosta*, the plant growth in Jingmen and Sheffield generally has no significantly difference during the same phase. Compared with other three plant species, *Hosta* grows more slowly both in Jingmen and Sheffield during all three different phases (Figs 3.45 to 3.47). And the significant growth difference is noted under different irrigation treatments both statistically and visually in the same phase. Such characteristic of growth may be caused by the special environment of LWS.

2) The difference in plant growth focuses more on the plant size rather than the plant leaf number. In terms of plant size, the significant increase occurs in the first and the third phases with the positive increase in the first phase while negative one in the third phase. This is because growth pressure posed by the environment in the first phase has not gone beyond the limits of plant growth; while the harsh environment in the second phase dramatically limited the plant growth. However, in the third phase, the plant growth had been dramatically slowed down by the combination of hostile environment and the natural dormancy. Plants during the third phase reduce their sizes especially in terms of the plant spread. But it could also be noticed in the Figs 3.45 to 3.47 that this growth reduction could be slowed down by high-level soil moisture content.

3) Although plant growth has the optimal irrigation treatment at statistical level in different phases, there is no significant visual difference observed by the author. However, the wet environment could better promote the *Hosta*'s growth compared with other treatments throughout the whole experiment in 2018 (Table 3.16). In addition, the plant growth of *Hosta* is slower than other plant species.

Table 3.16 The optimal and economic irrigation treatment for *Hosta* 'Blue Mouse Ears' in single species plant scheme in LWS in different cities (Exp1. in 2018)

TIME	JINGMEN (OPTIMAL)	JINGMEN (ECONOMIC)	SHEFFIELD (OPTIMAL)	SHEFFIELD (ECONOMIC)
Phase 1	Dry treatment	Wet treatment	Dry treatment	Dry treatment
Phase 2	Wet treatment	Wet treatment	Dry treatment	Dry treatment
Phase 3	Medium treatment	Medium treatment	Wet treatment	Wet treatment

3.3.2.3 *Heuchera* 'Marmalade'

For *Heuchera*, 1) The general plant growth of *Heuchera* is greater in Jingmen than in Sheffield. The growth of plant size in Jingmen is larger than the Sheffield in each phase, except for the plant spread in the second phase (Figs 3.45 and 3.46). Conversely, the plant leaf number is generally greater in Sheffield than that in Jingmen, especially in the second phase when significant difference shows. Therefore, this potentially illustrates a characteristic of *Heuchera*'s growth in LWS environment, which is that the environment may not be the main factor influencing plant size growth. However, it still should be noticed that the aesthetic rating of *Heuchera* could be dramatically affected by the environment that changes plant leaf number more than the plant size.

2) The growth rate of plant leaf number is closely related to the climatic changes. The maximum and minimum increase rates of plant leaf number come in the same time (second phase) (Fig 3.47). The Table 3.12 shows that the plant leaf number has relatively stronger correlations with the temperature and precipitation amount. This indicates that *Heuchera* is sensitive to the sunlight intensity especially in the open areas such as LWS. Although a higher intensity could promote the growth of plant leaf number, the continuous exposure to sunlight of that intensity over a long time can cause plant leaves to wither and to be damaged.

3) The optimal irrigation treatment is different in different countries. *Heuchera* in the environment of Jingmen prefers the relatively wet environment while in Sheffield, it prefers the relatively dry soil moisture content (Table 3.17). Based on Table 3.12, this may be the result of the combining impact of both the temperature and relative humidity. Plants in higher temperature with lower humidity such as Jingmen, prefer to absorb the water from the growing medium, while in the environment with lower temperature and heavier rainfall, plants could absorb additional water through large size leaves.

Table 3.17 The optimal and economic irrigation treatment for *Heuchera* 'Marmalade' in single species plant scheme in LWS in different cites (Exp1. in 2018)

TIME	JINGMEN (OPTIMAL)	JINGMEN (ECONOMIC)	SHEFFIELD (OPTIMAL)	SHEFFIELD (ECONOMIC)
Phase 1	Wet treatment	Medium treatment	Wet treatment	Wet treatment
Phase 2	Dry treatment	Medium treatment	Wet treatment	Wet treatment
Phase 3	Wet treatment	Medium treatment	Medium treatment	Wet treatment

3.3.2.4 *Hedera helix* L.

For *Hedera*, 1) The plant growth is generally greater in the Jingmen than that in Sheffield. The change of plant size is generally larger in Jingmen than that in Sheffield during all phases, while no significant difference is noticed in the plant leaf number between those two cities (Figs 3.45 to 3.47).

2) The trends of plant size growth and leaf number increase are opposite. The growth of plant size decreases over time, while the number of leaves rises. This may be because the plant size and leaf number have different levels of susceptibility to the environment changes and the plant size is more susceptible than the plant leaf number (Table 3.13).

3) The optimal irrigation treatment in both Jingmen and Sheffield is the wet environment in all phases.

3.3.3 Plant Dieback

The dieback was observed in all plant species on the LWS in 2018 experiment. It was the *Hosta* that has the most serious dieback than the other plant species with the worst dieback happening in the third phase. The main reason behind is the combination of the natural dormancy and the plant's preference for shadow. The decease of plant growth in Sheffield is more than that in Jingmen. Due to the different climates, Sheffield has lower temperature and shorter sun hours than the Jingmen (Figs 3.41 to 3.44).

In addition, even the plants of high drought tolerant capacity such as *Vinca* and *Hedera* have dieback in the LWS environment mainly in the third phase in Sheffield. This might indicate that the climate becomes the key factor influencing plant growth when the temperature and sun hours fall below a certain threshold for plants growing in the LWS environment. This may result from the characteristics of LWS environment, where limited growing medium makes the temperature in the root lower than the temperature of soil in the ground. And it finally leads to the slower growth and even dieback.

The reduction in leaf numbers in *Vinca* and *Hedera* mainly occur in the first phase in the Sheffield. However, it should be noticed that the plants still grow in this phase. Based on visual observation on the field work, Tables 3.3 and 3.9, it can be seen that the decrease is mainly caused by slowing growth rate of small leaves and the loss of large leaves. However, this problem can be alleviated by soil of higher moisture content. Considering the correlation analysis, although all those plants have high drought tolerant capacities, the reasons for dieback vary. *Vinca* was suppressed mainly by the relative humidity, while *Hedera* by the temperature.

3.3.4 Plant Aesthetic Rating

In general, the change of plants' aesthetic rating is greater in Jingmen than that in Sheffield statistically. However, those differences could be visually noticed only in some plant species.

The aesthetic rating of plants is generally greater in the first and the third phases than that in the second phase except for *Hosta*, which experiences natural dormancy in the third phase. All plant growth is significantly inhibited by the environment in the second phase. In addition, the leaves in this phase starts to turn yellow and wither, which dramatically affects the aesthetic rating.

3.3.5 Hypotheses

3.3.5.1 The plant growth and development will be affected by water availability (Dry, Medium, or Wet) and position on the wall.

The data supports this hypothesis. As discussed in the previous sections, in LWS environment, difference in irrigation treatments has significant influences on plant growth performance (including plant height, spread, leaf number, etc.). Statistical analysis (Figs 3.45 to 3.48) shows that, in the end of each phase (Day 60), for all the four plant species, statistically significant differences in growth were noted under different irrigation treatments ($p < 0.05$). However, they were mainly visually reflected in the change of plant size rather than of the leaf number (even leaf number change was still statistically significant). In addition, plant's growth performance changes with its capacity of drought tolerance. Higher drought tolerance would lead to the plant's higher sensitivity to the water availability. Therefore, for plants with relatively high drought tolerance like *Vinca* and *Heuchera*, compared with other plant species, irrigation treatment had more influence on their growth. This is because those kind of plant species have stronger ability to grow and develop when water might be limited (i.e., a higher water use efficiency), and can maintain some growth, despite some limitation in water supply within the growing medium. Another reason is that for plants with high drought tolerance, when supplied with sufficient water from growing medium, their metabolic activities will be more efficient. In this experiment, environment with higher water availability brought better growth performance of plants (mainly in plant size). In addition, however, that plant's water consume efficiency is also significantly impacted by environment changes, especially in LWS environment where plants are put above the ground on the wall. For example, in the second phase, improperly high sunlight intensity and long period of high temperature would force plants to close stomata, entering a status of "noon dormancy" and thus cause a slowdown in growth rate even in wet environment at noon time (Figs 3.45 to 3.47). This mechanism has also been proved by many other researchers (Heath and Meidner, 1957; Rees, 1961; Wuenscher and Kozlowski, 1971).

The factor of plant's position on the wall of LWS also has a certain impact on plant growth, but those effect is generally weaker than the factor of plant species. For plants with relatively high drought tolerance such as *Vinca* and *Hedera*, the position in LWS exerts greater influence on plant growth. Plants in the middle layers, instead of the top or bottom layer of LWS, generally had the greater plant height. However, this relative higher is not statistically difference, but it is worth further research. A possible hypothesis is that either the environment (position in the top or bottom layer in LWS) inhibits the plant growth (strong sunlight intensity on the top or too much water content on the bottom of the LWS) or that the middle layer environment is more favourable to plant growth. But for plants that favour moist but well-drained environment like *Heuchera*, the lower the position in the LWS the better it will grow. However, this phenomenon does not indicate that shady plant species will grow better under the moist environment such as the bottom level of LWS. For instance, the growth of *Hostas* show no significantly different among different positions in LWS when they applied the same irrigation treatment. It is not clear that whether this performance of *Hosta* is influenced by the natural dormancy later in the summer. More experiments are needed to find out their relationship.

3.3.5.2 The effects of irrigation treatments will vary, depending on local climate conditions (Sheffield, the United Kingdom vs. Jingmen, China).

The data support this hypothesis. Local climatic factors seem to have a strong influence on growth and quality. In terms of the optimal irrigation, the location differences could affect plant growth rates, but do not change the size ranking of plant growth under different irrigation treatments in the most cases. In other words, the difference in plant size between different irrigations can be increased or decreased, but does not change the ranking. The optimal irrigation treatment is the same in both cities, and the difference is only how much it will increase. For instance, the wet treatment is the optimal irrigation in the first and the third phase to allow *Vinca* to achieve the greatest growth in both Jingmen and Sheffield. However, there is no similar trend for plant growth under the economic irrigation. Location is not a major factor in optimal irrigation treatment, but a major factor in economic irrigation treatment.

The factor of climate which caused by different cities could not only enhance the growth of plants, but also significantly affect the aesthetic rating of plant. However, according to the statistics, this effect is mainly to enhance the negative effects of plant dieback. Therefore, it is suggested that the location of the LWS is also an important factor for plant aesthetic rating if the plant is dormant.

In addition, although the correlation value between the growth of the four plant species and climate information are generally moderate and weak in the correlation analysis (Tables 3.10 to 3.13), it cannot be inferred that the growth of the plants is completely independent of the climatic differences. The impact of climate on plant growth is probably decided by multiple meteorological factors together.

3.3.5.3 Species with large leaves and high shade-adaptation (e.g., *Hosta*) will perform less well compared to those that can adapt to drier conditions (e.g., *Vinca*).

This hypothesis also generally supported. It was evident that dieback was rarer in species better adapted to drought. For *Hosta*, (drought susceptible) however, almost in all phases, it experienced a certain degree of dieback; a point reflected in aesthetic ratings. But there are multiple causes. On one hand, long-time direct exposure to sunlight in open LWS environment inhibits plant growth. On the other hand, natural dormancy also contributes to loss of foliage. It's also worth attention that if plant has only one feature of large leaves, its growth will not be inhibited significantly by LWS environment. For example, although *Heuchera* may not be as highly tolerant to drought as *Vinca*, there was no significant difference in plant spread noted between them. Besides, *Heuchera* had more growth in leaf number than *Vinca*.

3.4 CONCLUSION

The results of this experiment give strong support to the importance of irrigation treatment for plant growth performance in single species planting scheme in LWS. Although it overall suggests more moist soil is conducive to better plant growth, in fact, the conclusion of this experiment confirms that multiple factors are important. Factors such as species choice, time of season, position in the LWS and location all impacted on plant parameters as well as irrigation levels.

Plant's different biological indexes (e.g., plant height, spread, leaf number, aesthetic performance) respond differently to the same irrigation treatment, which means that influences on them are not uniform. For example, soil with high moisture content is beneficial to higher plant height and wider plant spread, but it, on the contrary, leads to slower increase in leaf number (e.g., *Hedera* in phase 1). This effect difference means the optimal irrigation treatment should not always focus on any particular aspect, be it higher plant height or more leaves. For example, in terms of plant size and leaf number, different plant species has different focus in order to achieve the best aesthetic performance. For *Heuchera*, more leaves will bring better visual pleasure; while for *Vinca*, bigger plant size leads to higher aesthetic rating. Therefore, the optimal irrigation treatment should be chosen based on both the increase it will bring to each plant biological index and the life cycle of the LWS as a whole.

Plant's position in LWS does have a certain impact on plant growth, but current LWS experiment cannot prove whether the impact is significant or not. Moreover, different plant species are influenced by their positions in LWS differently. So, to discover the relationship between plant's position in LWS and its growth, further experiments are needed.

In author's opinion, plants with natural dormancy are not suitable for LWS, because they wither in that special period (e.g., Phase 3 in this experiment (September to October 2018)), resulting in a significant decline in aesthetic rating. But this decrease in aesthetic rating cannot be changed by different irrigation treatments. Although certain irrigation treatment can slow down the decrease rate to some extent, the overall aesthetic performance does not reach the pleasant level.

Key Points in Experiment 1

- Growth is affected by irrigation level, but climate also alters the responses plants display.

- The two more drought tolerant species *Vinca* and *Hedera* tended to grow better than those considered less drought tolerant (*Hosta* and *Heuchera*).

- Care must be taken when comparing plant parameters – some plants expressed their growth laterally not vertically for example.

- There was some suggestion of trade-offs between extension growth and numbers of new leaves.

- All plants including the *Vinca* did not grow extensively, suggesting the conditions including the irrigation levels are inhibiting excessive plant growth – this could be an advantage on LWS where excessive shoot growth could relate to more pruning and thus more maintenance costs.

CHAPTER 4: EXP 2. THE EFFECT OF MIXED PLANT SPECIES CHOICE, IRRIGATION, LOCATION AND TIME OF GROWTH

Experiment 1 demonstrates plant performances when different species are exposed to different irrigation regimes, but plants of each species were maintained within individual modules. What happens when plants of different species have to compete for water within the same module? This was the objective of Experiment 2, to determine how growth performance was affected by irrigation regime, but where individual plants of one species may have to compete for water, light, and nutrients with other species. There are various vegetation planting schemes of LWS projects worldwide and this inter-species competition may be common. However, current research on this topic is limited. Experiment 2 serves as a pioneer to explore the plant inter-species competition in LWS.

As before, the experiment tests the influence of irrigation (water availability), location (cities) and time (different seasons) on plant development, but in this case under mixed species planting schemes.

The experiment tested the following hypotheses:

- Some species would outcompete others in the mixed species planting when grown in the same LWS unit.

- Levels of irrigation supplied, will affect the levels of competition plants might experience.

4.1 MATERIAL AND METHODS

4.1.1 Experimental Design

Due to the limited size of the LWS in experiment, only 3 plant species were picked out based on perceivable different water requirements, which are *Vinca major* 'Variegata', *Hosta* 'Blue Mouse Ears' and *Heuchera* 'Marmalade' (See Chapter 2.5). Most plants were the same plants used in Experiment 1 in 2018, the plants dead in the winter and deficient plants were replaced with new ones purchased from the local plant nursery. Due to the slow re-growth of the existing *Hosta*, 120 new *Hosta* individuals were purchased and applied in this research (60 for each experimental site). In conclusion, 60 individual plants of each species and a total of 180 plants were used in each experiment site.

Placing three different species in the one module was referred to as a mixed plant community (or 'community' for short). The new plant community designs were proposed to avoid any "Edge Effect". This is where plants at the edge of a mono-crop might behave differently because they are exposed to more light, wind and lower relative humidity and temperature – simply because they are at the edge of the crop or plant community. To avoid any bias on this account the species order was changed to ensure that the same species was not always at the edge. The final design of four plant communities is shown in Table 4.1 and Fig 4.1. Those design of plant community is based on the characteristics of the LWS unit which has 5 layers, each allowing 3 plant species. Therefore, plant species is placed on the left, middle and right side of each layer of LWS unit. Each LWS unit supports 15 individual plant and 12 independent LWS units (see Chapter 2.3) were used for each experiment site.

Table 4.1 The design of four different plant communities

	PLANT COMMUNITY 1			PLANT COMMUNITY 2			PLANT COMMUNITY 3			PLANT COMMUNITY 4		
Layer 1	Vinca	Hosta	Heuchera	Hosta	Heuchera	Vinca	Heuchera	Vinca	Hosta	Heuchera	Hosta	Vinca
Layer 2	Heuchera	Vinca	Hosta	Vinca	Hosta	Heuchera	Hosta	Heuchera	Vinca	Vinca	Heuchera	Hosta
Layer 3	Hosta	Heuchera	Vinca	Heuchera	Vinca	Hosta	Vinca	Hosta	Heuchera	Hosta	Vinca	Heuchera
Layer 4	Vinca	Hosta	Heuchera	Hosta	Heuchera	Vinca	Heuchera	Vinca	Hosta	Heuchera	Hosta	Vinca
Layer 5	Heuchera	Vinca	Hosta	Vinca	Hosta	Heuchera	Hosta	Heuchera	Vinca	Vinca	Heuchera	Hosta

Figure 4.1 The example of arrangement of plants (*Vinca*, *Hosta*, *Heuchera*) on each LWS containers (Exp 2 in Jingmen, China)

Before the start of the Experiment 2 in 2019, the LWS units were disinfected. The disinfection treatment method is removing all plants (from Exp 1) and growing media from the LWS container and exposing the container and growing media to natural sunlight. The plants, were put together in large trays over winter and prevent the root from freezing during the winter. All plants were re-pruned to a similar size in each place (15 x 15 cm, h x b) before the recommencement of the experiment (see Chapter 2.5). Plants were graded and re-randomised to help avoid bias due to any residual effects from Exp. 1. The coco-based growing medium (100% coco flakes, Coco Plus Professional Plus, Attn. CANNA UK, London, UK) was also selected and used throughout the whole Experiment 2.

The Experiment 2 was divided into 2 phases (two months per phase) in each experimental site. This made it possible that the effect of the environmental changes in different seasons can be measured. These two repeated experiments in 2019 are named Phase 1 and Phase 2 (treatments summarised in Table 4.2). The data originally designed for a Phase 3 was unable to be recorded in full due to the facility issues and the Covid-19 pandemic and subsequent lockdowns The first phase started from 1st May 2019 to 30th June 2019. It included a range of average daily temperatures from 6.4 to 21.2°C in Sheffield and 14.8 to 28.3°C in Jingmen. This period is also a naturally slow-growing season for the selected ornamental plants; The second phase started from 1st July 2019 to 30th August 2019. It included a range of average daily temperatures from 12.9 to 26.1°C in Sheffield and 22.4 to 31.9°C in Jingmen. This period has relatively high temperature and long-time sunlight compared with other phase which put the pressure on the plant growth. Three irrigation treatments (i.e., dry treatment, medium treatment, and wet treatment) and plants were set as below (Table 4.2). Those three irrigation treatments include the Dry, the Medium, and the Wet Treatment (see Chapter 2.4.1). The irrigation system is the same one that used in Experiment 1 in 2018 (see Chapter 2.4.2).

Table 4.2 The schedule of the time arrangement, plant locations in the LWS and irrigation treatments in Experiment 2

PHASES	TIME	PLANT LOCATION AND IRRIGATION TREATMENT									
Phase 1 (spring)	1st May 2019	Layer	Wall 01			Wall 02			Wall 03		
		L1	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
	To	L2	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L3	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
	30th June 2019	L4	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
		L5	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
			Wall 04			Wall 05			Wall 06		
		L1	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
		L2	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
		L3	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L4	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
		L5	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
			Wall 07			Wall 08			Wall 09		
		L1	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L2	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
		L3	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
		L4	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L5	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
			Wall 10			Wall 11			Wall 12		
		L1	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca
		L2	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta
		L3	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera
		L4	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca
		L5	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta
Phase 2 (summer)	1st July 2019	Layer	Wall 01			Wall 02			Wall 03		
		L1	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
	To	L2	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L3	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
	30th August 2019	L4	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
		L5	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
			Wall 04			Wall 05			Wall 06		
		L1	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
		L2	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
		L3	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L4	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
		L5	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
			Wall 07			Wall 08			Wall 09		
		L1	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L2	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
		L3	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera
		L4	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta
		L5	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca	Hosta	Heuchera	Vinca
			Wall 10			Wall 11			Wall 12		
		L1	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca
		L2	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta

		L3	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera
		L4	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca
		L5	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta	Vinca	Heuchera	Hosta

* Red colour for dry treatment, yellow colour for medium treatment, green colour for wet treatment

4.1.2 Data Collection and Statistical Approaches

The climate data about Sheffield and Jingmen came from the same weather station as in the Experiment 1. In terms of the soil moisture data, 12 SM150T sensors were also used in the LWS as in the Experiment 1. The physiological data about plant growth also focused four different categories of plant characteristics (see Chapter 2.7). The measurement days for each experiment phases in 2019 are: Phase 1 is on the date 1, 15, 31 May, 15, 30 June; the Phase 2 is on the date 1, 15, 31 July, 15, 31 August.

Statistical Approaches

Statistical analysis involves four independent variables (irrigation treatments, plant species, location, and time) and explored any effects on plant growth. The Repeated Measures ANOVA (IBM® SPSS® Statistics 25) was applied to find the significance between different irrigation treatment and time on plant growth of different species in the mixed species planting scheme. The Simple Linear Regression (IBM® SPSS® Statistics 25) was used to analysis the effect of different climate factors on growth of plant in the mixed species planting scheme. All the graphs below use the transformed data to make it easier for the reader to understand. An alpha level if 0.05 was used for all statistical analysis.

4.2 RESULTS

4.2.1 *Vinca major* 'Variegata'

***Vinca* – Jingmen, China**

1) The changes of plant height

In Jingmen, there was a significant difference in the changes of *Vinca*'s height in both phases ($p < 0.05$) (Fig 4.2). Overall, plants under all treatments grew more vigorously during Phase 1 than during Phase 2.

At each phase, however, effects from different treatments were noted. During the first phase, *Vinca*'s height under the medium and the wet treatments grew to a greater extent than those under the dry treatment ($p < 0.05$, Bonferroni). During the second phase though, the wet treatment alone led to the greatest growth of plant height ($p < 0.05$).

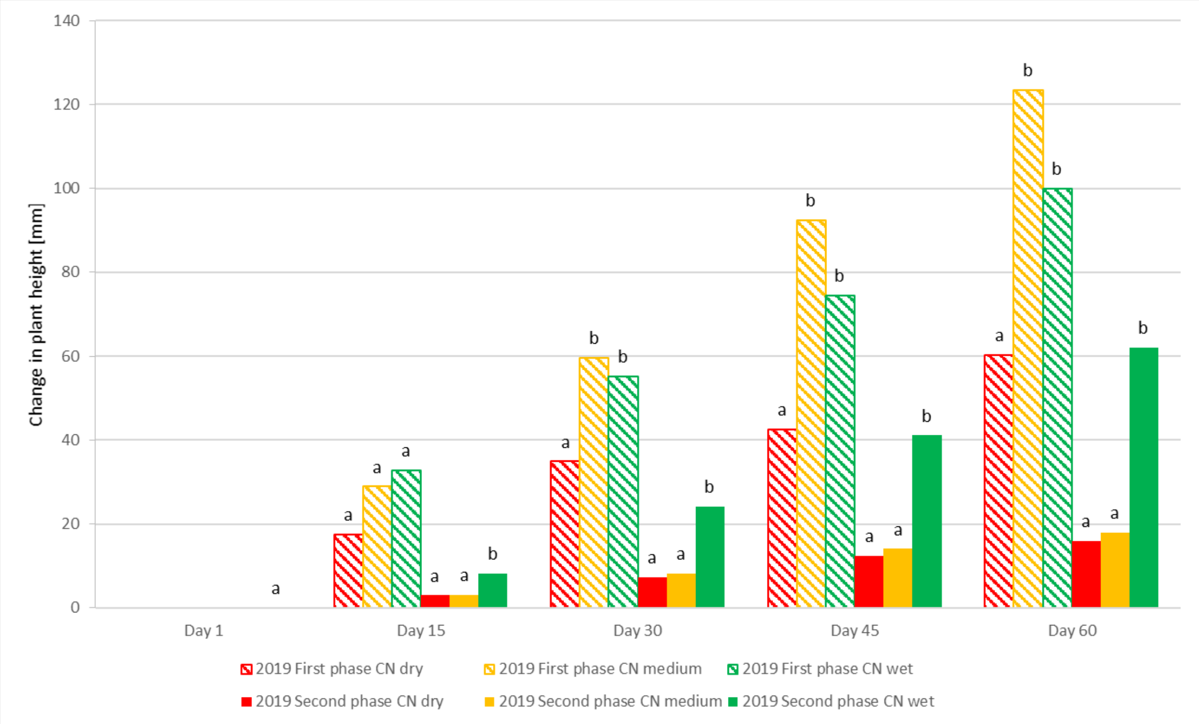

Figure 4.2 The mean change in plant height of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

2) The changes of plant spread

The plant spread was generally greater in Phase 1 (Fig 4.3) and the plants under the medium and the wet irrigation treatments out-grew those under the dry treatment ($p < 0.05$). It was not the same, however, in the second phase, when the increase of plant spread under the medium irrigation treatment was significantly less than those under the dry and the wet irrigation treatments ($p < 0.05$).

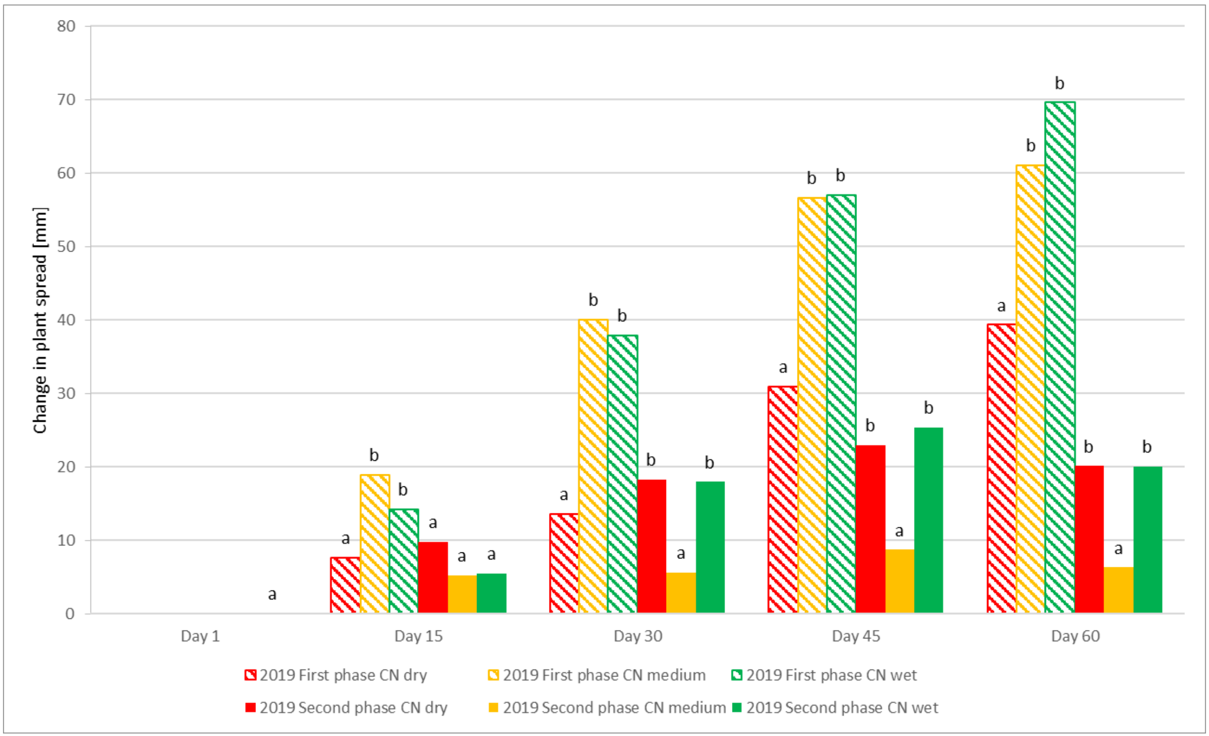

Figure 4.3 The mean change in plant spread of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

3) The changes of numbers of plant leaves

Generally, the plants developed the most leaves in the first phase (Fig 4.4). And a significantly increased number of leaves were present on the plants under the medium treatment by the end of the first phase ($p < 0.05$). This treatment during this phase also corresponded with a huge number of the large leaves (26.15 per plant, Table 4.3) compared to other treatments. During the second phase, the overall leaf number was optimized under the wet irrigation treatment ($p < 0.05$). This treatment corresponded with a large number of the middle (13.9 per plant) and the small leaves (14.4 per plant) compared to other treatments.

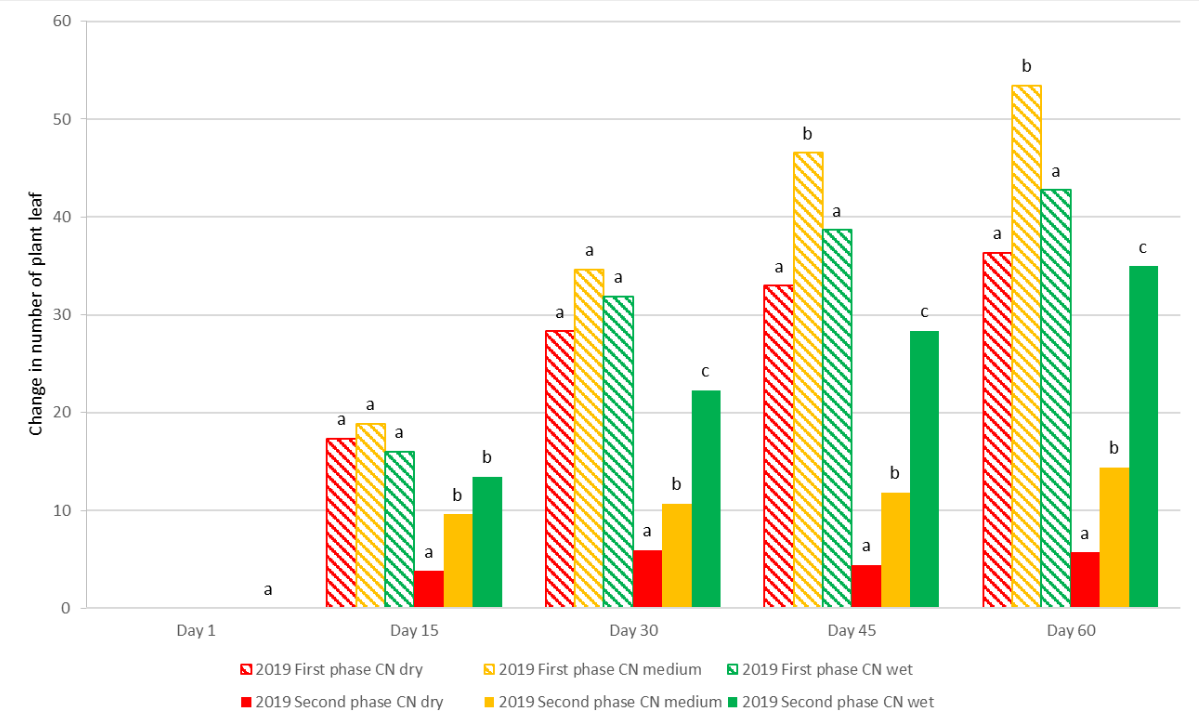

Figure 4.4 The mean change in number of the plant leaves of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

Table 4.3 The mean change in numbers of the plant leaves of *Vinca major* 'Variegata' of different sizes under different irrigation treatments in Jingmen, China (Exp2. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2019 First phase CN dry	36.35	3.09	12.55	0.83	7.30	2.33	16.50	1.28
2019 First phase CN medium	53.45	4.93	26.15	3.50	15.35	1.69	11.95	1.73
2019 First phase CN wet	42.75	4.06	21.25	2.00	13.35	2.24	8.15	1.58
2019 Second phase CN dry	5.70	2.20	2.50	1.38	0.00	1.32	3.20	1.27
2019 Second phase CN medium	14.40	2.77	5.65	1.58	1.70	1.58	7.05	2.34
2019 Second phase CN wet	34.95	6.18	6.75	1.57	13.85	3.41	14.35	2.08

4) The changes of plant aesthetic ratings

The plant quality was deemed considerably high both in the first and the second phases of the summer experiments (Fig 4.5). The medium and the wet irrigation treatments optimised the plant quality in the first phase ($p < 0.05$), but only the wet region optimised the plant quality in the second phase ($p < 0.05$). Fig 4.6 presents similar growth rate of the changes in aesthetic rating in relative value and absolute value, which both reflected significant improvement of the aesthetic rating of plants in the wet treatment.

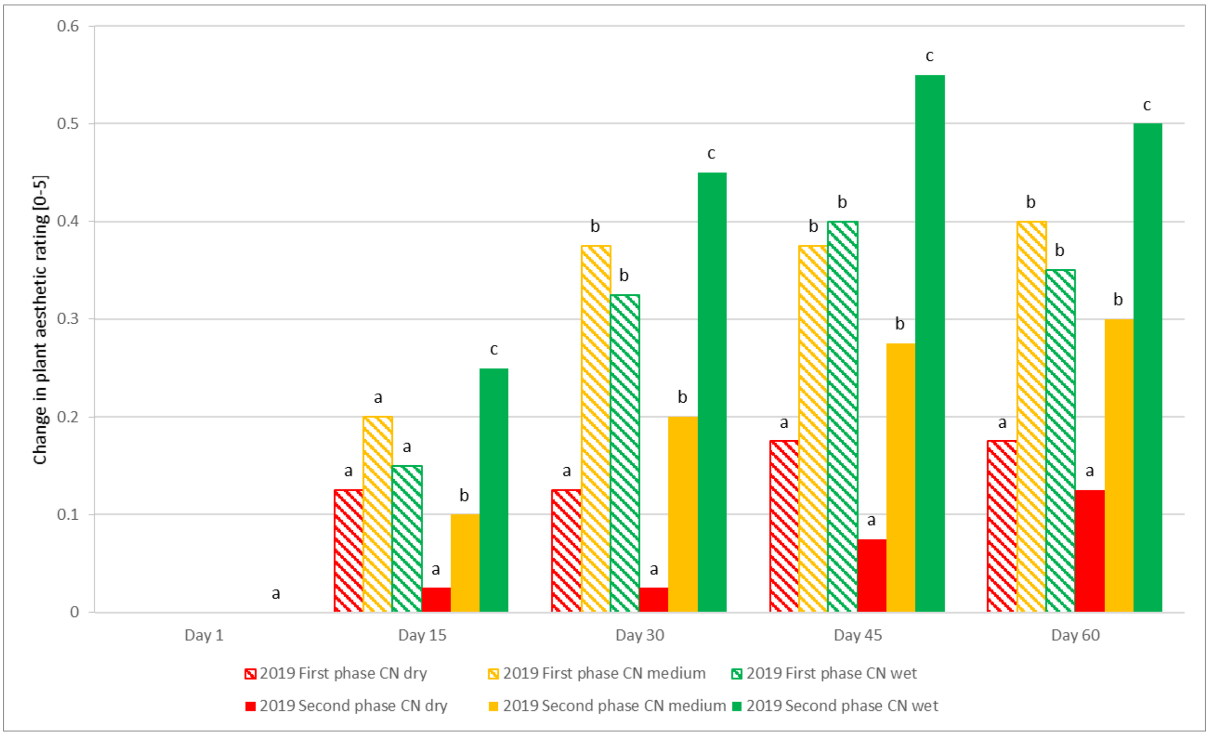

Figure 4.5 The mean change in plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. The letters on the graph denote difference from the transformed values)

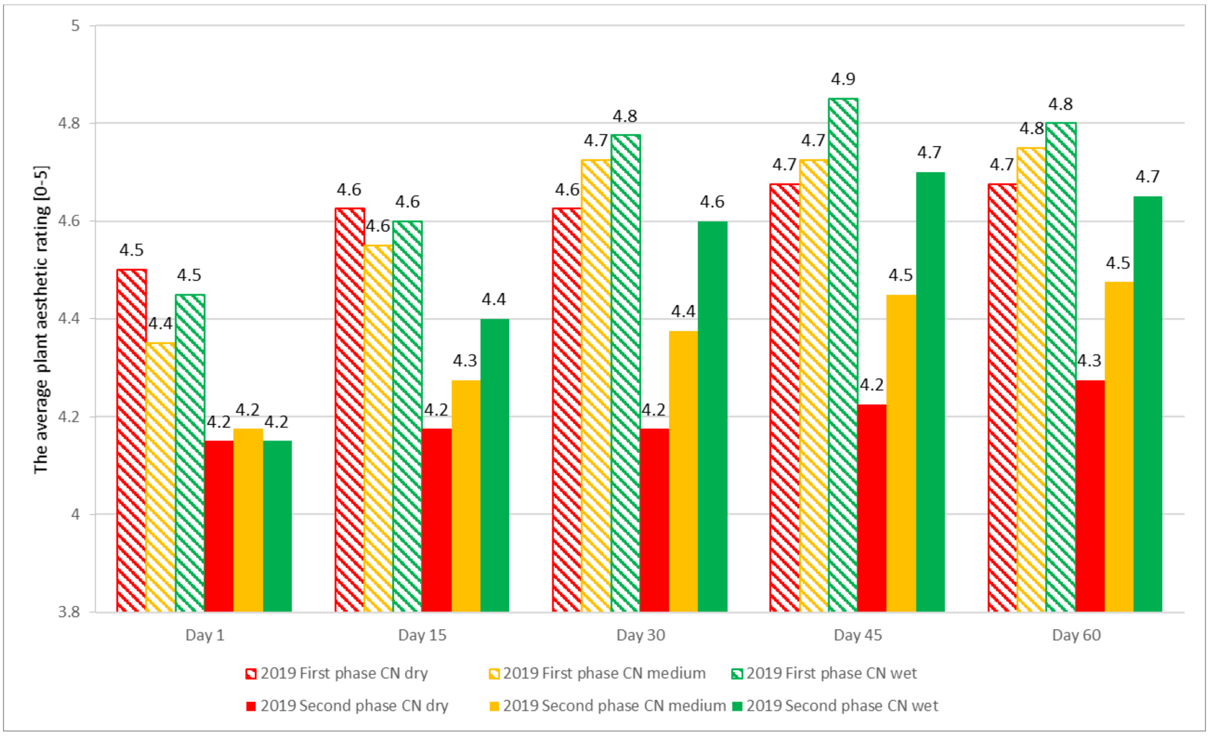

Figure 4.6 The mean value of plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Jingmen, China (Exp2. in 2019)

***Vinca* – Sheffield, United Kingdom**

1）The changes of plant height

In Sheffield, there was a significant difference in the changes of *Vinca*’s height in both phases ($p < 0.05$) (Fig 4.7). Overall, plants of all treatments grew much more vigorously in the first phase than in the second phase.

During the first phase, *Vinca*’s height under the wet irrigation treatment significantly out-grew those under the medium and the dry treatment ($p < 0.05$). In addition, the overall growth of plant height was much larger compared to the latter phase in summer. During the second phase, the medium treatment caused the lowest growth of plant height among all treatments ($p < 0.05$).

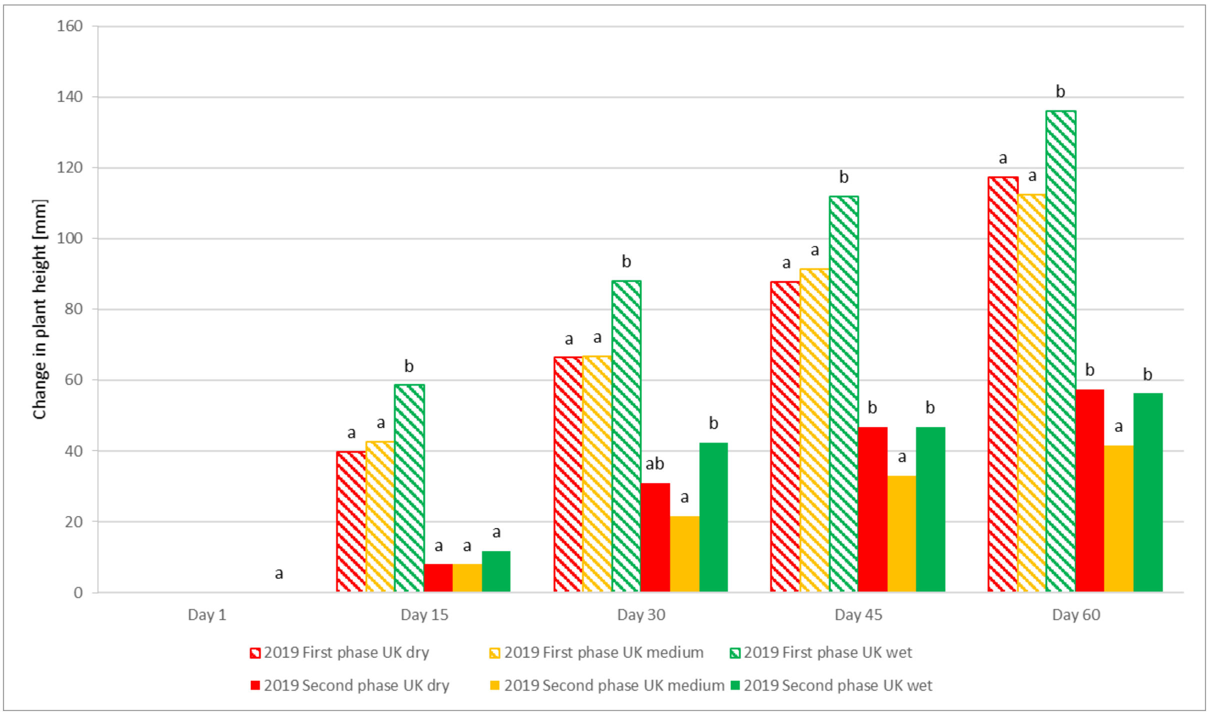

Figure 4.7 The mean change in plant height of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread

Generally, the plant spread was greater in the first phase (Fig 4.8), and the plants under the medium and the wet irrigation treatment had outgrown the dry treatment by the end of Day 60 ($p < 0.05$). In contrast, in the second phase, the plant spread was only significantly greater under the medium irrigation treatment ($p < 0.05$).

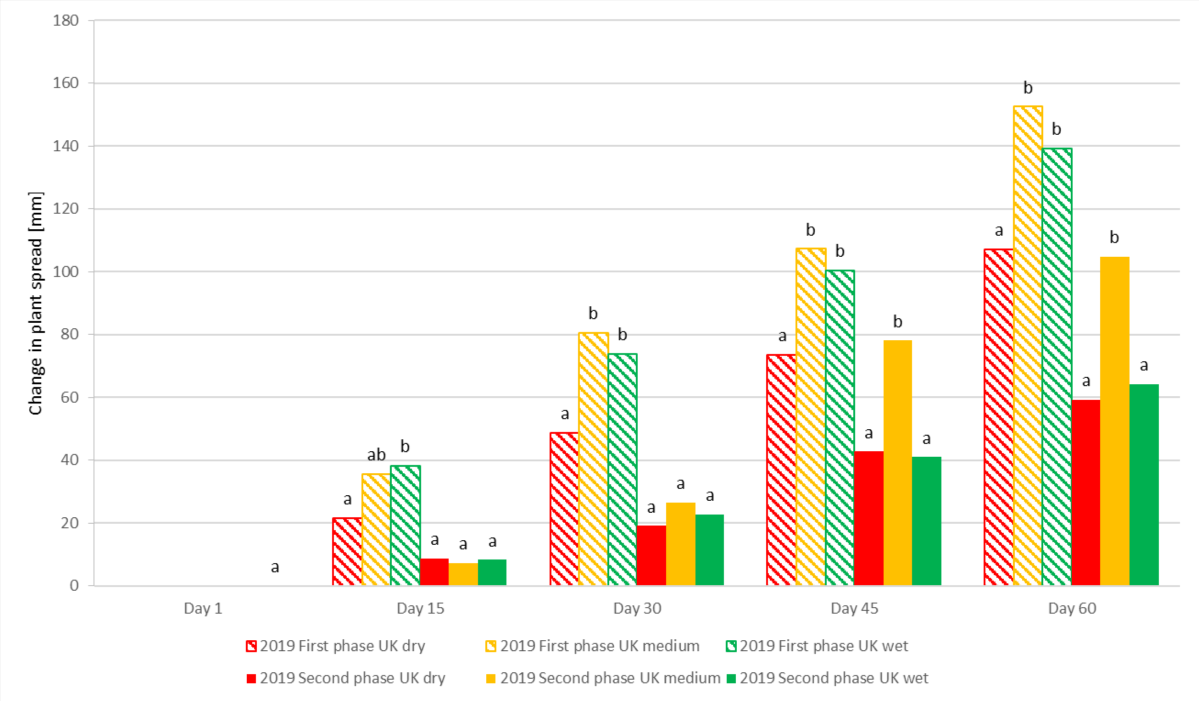

Figure 4.8 The mean change in plant spread of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

Generally, the plants developed a slightly larger number of leaves in the second phase than in the first phase (Fig 4.9), while a larger number of leaves were present on the plants under the dry and the medium treatment by the end of the second phase ($p < 0.05$). The large leaves had significantly increased under the dry (75.1 per plant) and the medium (70.5 per plant) treatments compared to the wet treatment. During the first phase, the overall leaf number was optimised under the medium treatment ($p < 0.05$), while the number of the large leaves were significantly promoted (100.8 per plant, Table 4.4) compared with other treatments.

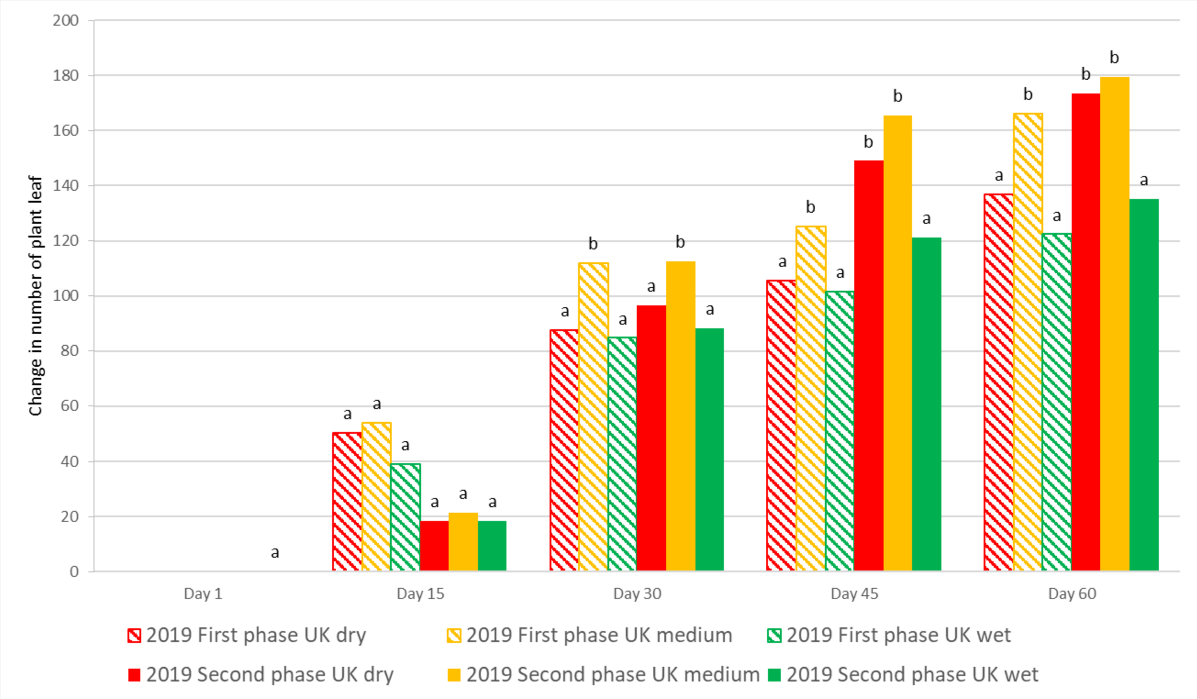

Figure 4.9 The mean change in number of plant leaves of the plant leaves of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

Table 4.4 The mean change in numbers of different size of the plant leaves of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2019 First phase CN dry	136.95	6.80	77.70	4.85	36.95	3.89	22.80	2.99
2019 First phase CN medium	166.10	10.83	100.75	6.97	45.15	5.67	20.20	2.42
2019 First phase CN wet	122.40	8.43	80.75	4.48	36.10	4.67	5.55	3.56
2019 Second phase CN dry	173.50	8.13	75.05	6.52	86.25	7.34	12.20	1.28
2019 Second phase CN medium	179.50	12.72	70.45	8.50	94.65	9.36	14.40	1.30
2019 Second phase CN wet	135.15	10.42	46.45	5.05	74.65	7.68	14.05	1.50

4) The changes of plant aesthetic ratings

The plant quality was deemed fairly high in the first and the second phase of the summer experiments (Fig 4.10). The medium irrigation treatment optimised the plant quality in the first phase ($p < 0.05$) while the dry and the medium treatment optimised the plant quality in the second phase ($p < 0.05$). As shown in Fig 4.11, however, the overall difference of plant aesthetic rating between different irrigation is not significant. But the trend of aesthetic difference is similar between those two figures: 1) the aesthetic rating is greater in phase 1 than in phase 2 and 2) the relatively dry growing media caused relatively higher aesthetic rating than the wet growing media.

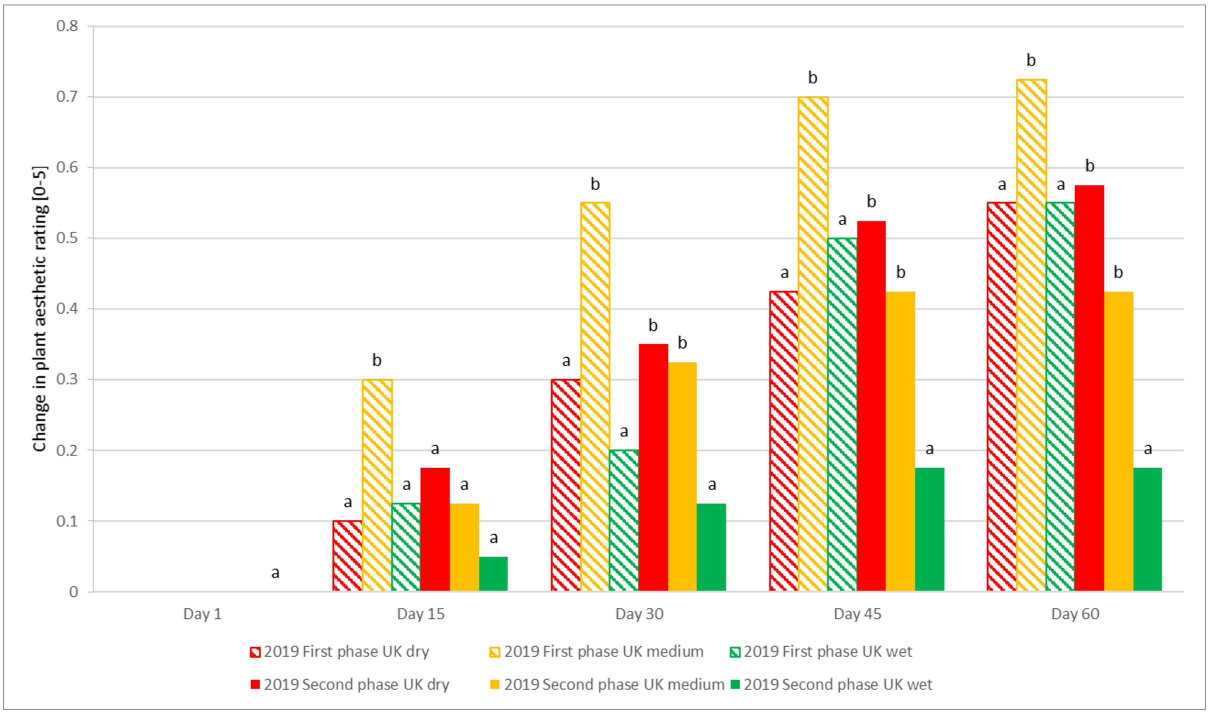

Figure 4.10 The mean change in plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. The letters on the graph denote difference from the transformed values)

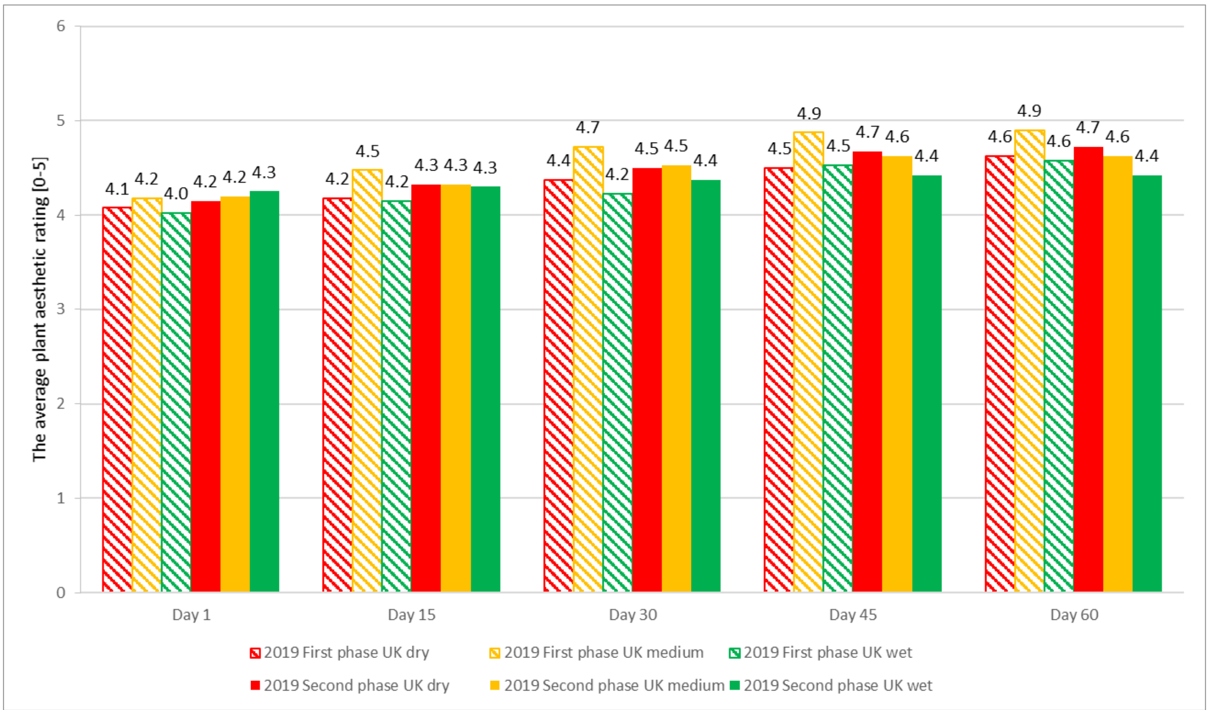

Figure 4.11 The mean value of plant aesthetic rating of *Vinca major* 'Variegata' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019)

4.2.2 *Hosta* 'Blue Mouse Ears'

***Hosta* – Jingmen, China**

1）The changes of plant height

In Jingmen, there was a significant difference in the changes of *Hosta*’s height in both phases ($p < 0.05$) (Fig 4.12).

Overall, the growth of the plants was greatest in the first phase, and the optimum treatments at this phase were the dry and the wet irrigation treatments, which are superior to the medium ($p < 0.05$). During the second phase, however, this was not the case. The wet treatment led to a significant loss of the plant growth (i.e., die-back). Therefore, the dry and the medium treatments that exceeded the wet treatment ($p < 0.05$).

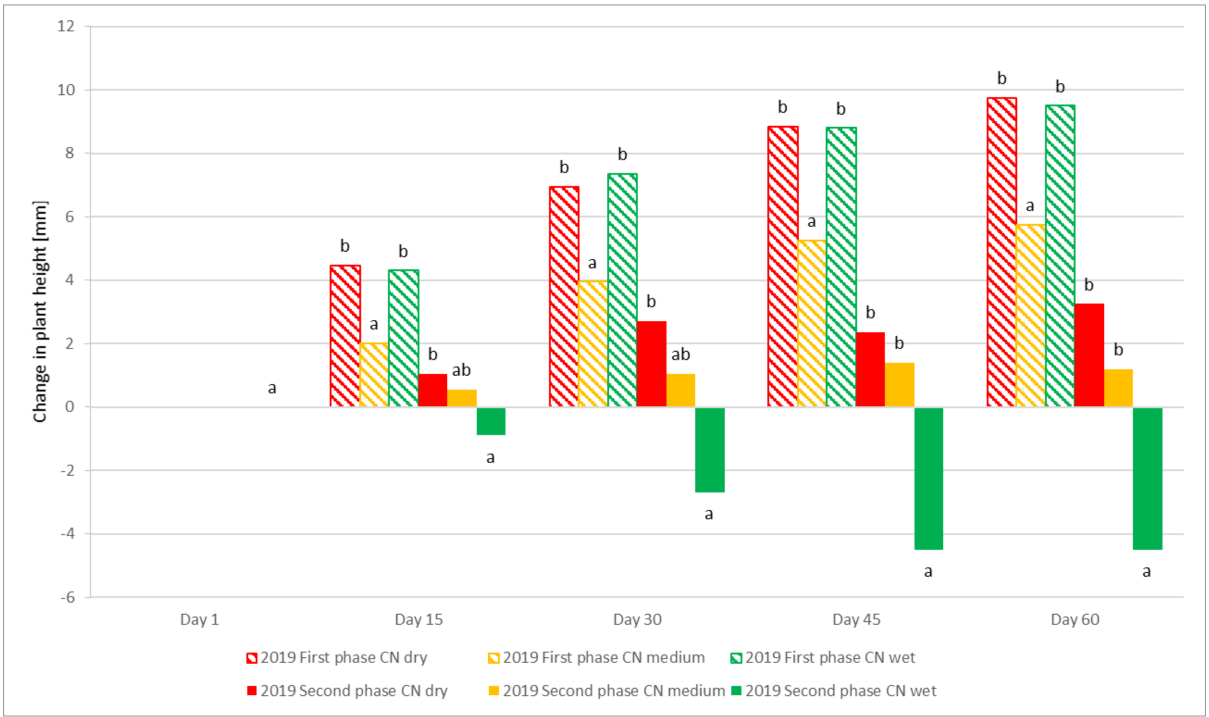

Figure 4.12 The mean change in plant height of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread

The growth of plant spread was generally greater in the first phase (Fig 4.13), but no treatment difference was evidently caused by water supply ($p > 0.05$). During the second phase, although growth was sizable in the wet irrigation treatment in the end of Day 60 ($p < 0.05$), the dieback was significant under all treatments in this phase.

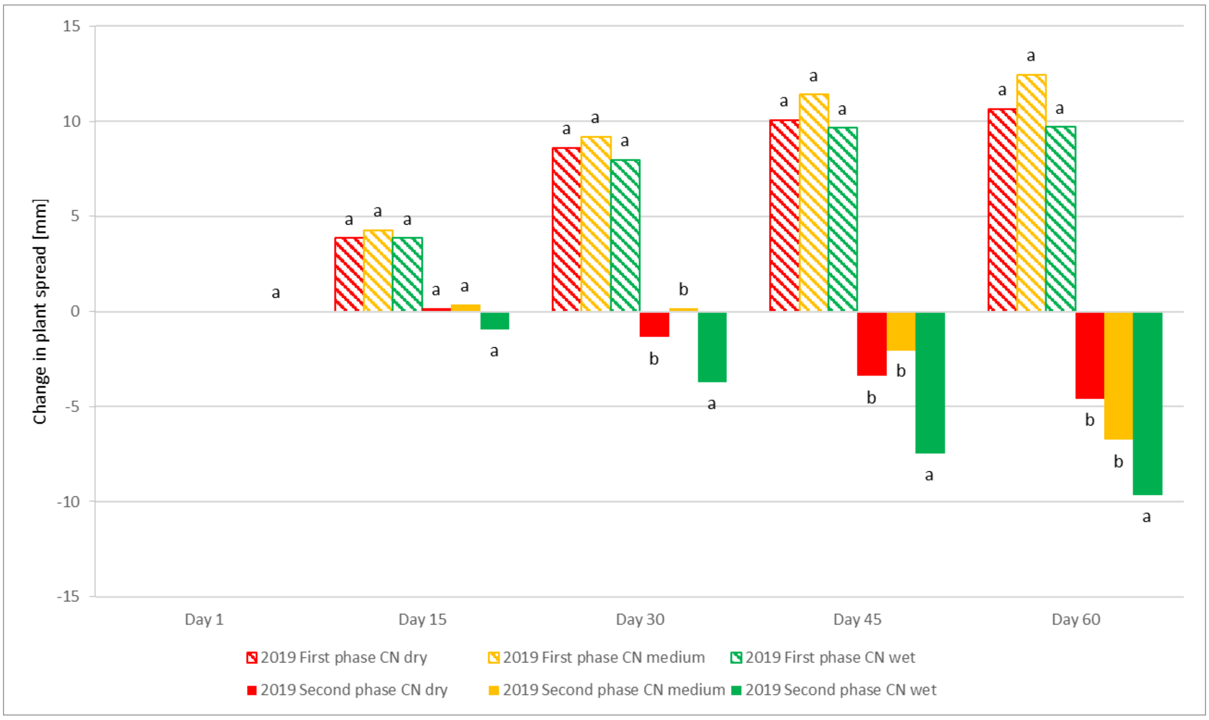

Figure 4.13 The mean change in plant spread of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

The development of plant leaves was significantly greater in the first phase (Fig 4.14), but no treatment difference was evidently caused by water supply by the end of the first phase ($p > 0.05$). During the second phase, an increased number of leaves were present on the plants under the dry and the medium treatments ($p < 0.05$). The large leaves increased by a large scale under the dry (0.80 per plant) and the medium (0.30 per plant, Table 4.5) treatment compared to the wet treatment. However, the dry treatment caused the plants to lose their leaves during this phase.

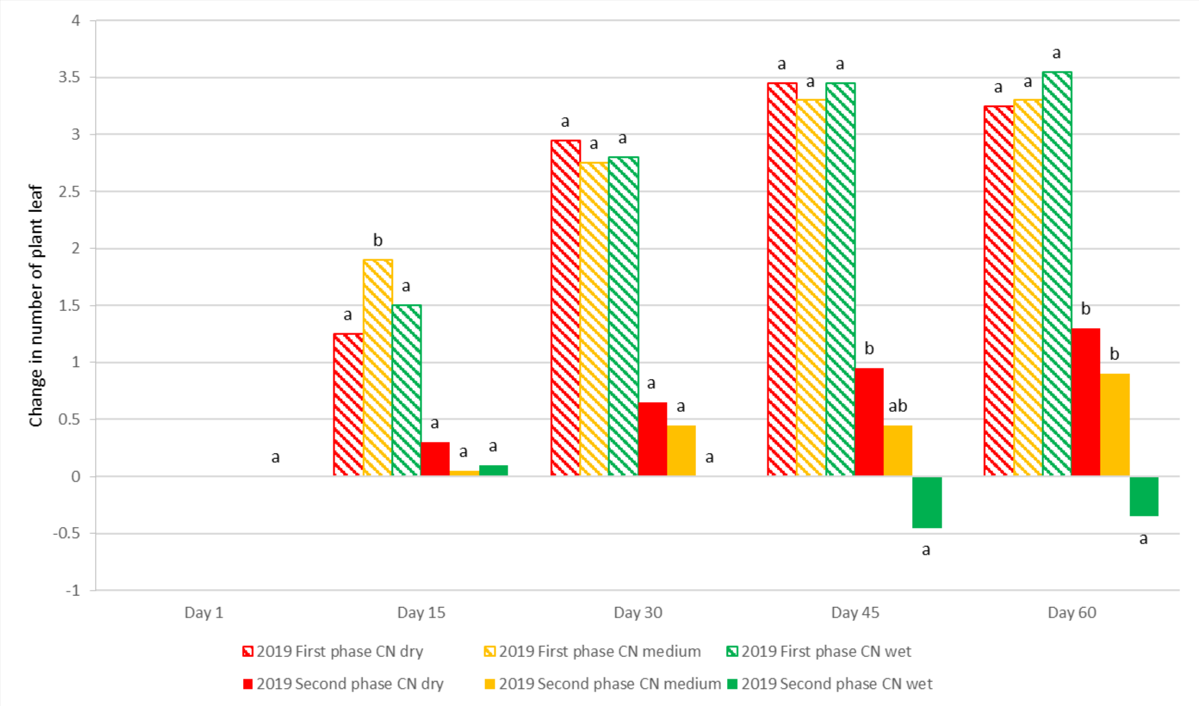

Figure 4.14 The mean change in number of the plant leaves of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen City, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

Table 4.5 The mean change in numbers of different size of plant leaves of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in the Jingmen City, China (Exp2. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2019 First phase CN dry	3.25	0.58	4.60	0.57	-1.50	0.44	0.15	0.28
2019 First phase CN medium	3.30	0.44	3.65	0.45	-0.85	0.39	0.50	0.20
2019 First phase CN wet	3.55	0.57	5.55	0.77	-2.05	0.72	0.05	0.39
2019 Second phase CN dry	1.30	0.39	0.80	0.45	0.50	0.20	0.00	0.00
2019 Second phase CN medium	0.90	0.45	0.30	0.16	0.60	0.44	0.00	0.18
2019 Second phase CN wet	-0.35	0.15	-0.85	0.32	0.40	0.23	0.10	0.20

4） The changes of plant aesthetic ratings

The plant quality was deemed greater in the first than the second phases of the summer experiments (Fig 4.15). The dry and wet irrigation treatments optimised the plant quality in the first phase ($p < 0.05$), but the dry and the medium treatments optimised the plant quality in the second phase ($p < 0.05$). The overall actual aesthetic rating (Fig 4.16) presents that the dry treatment in the first phase and the medium treatment in the second phase are the optimal treatment in terms of aesthetic rating of the plant.

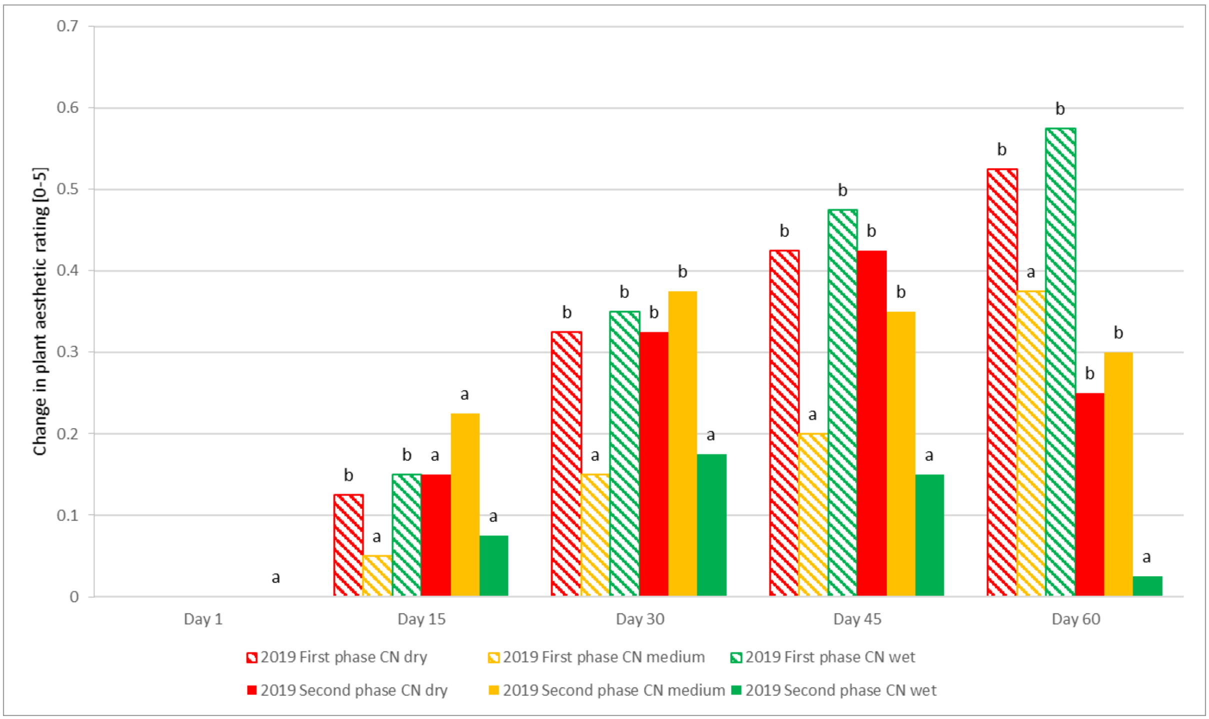

Figure 4.15 The mean change in plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen City, China (Exp2. in 2019) (NB. The letters on the graph denote difference from the transformed values)

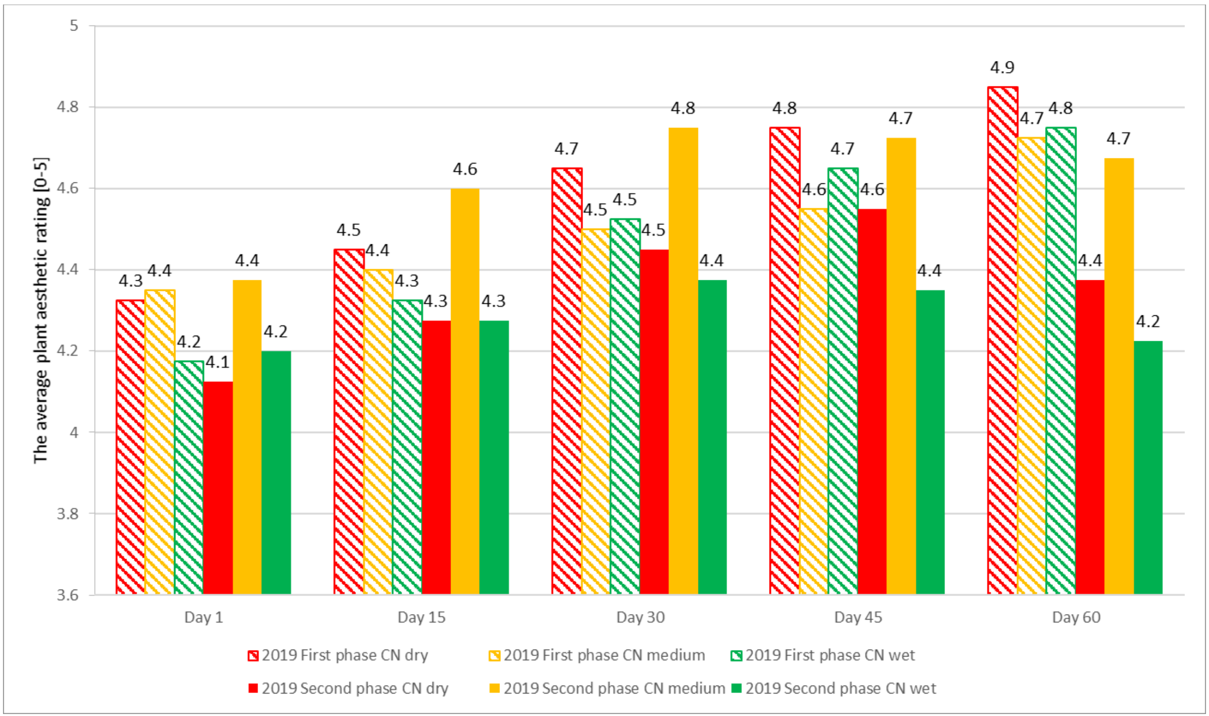

Figure 4.16 The mean value of plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Jingmen City, China (Exp2. in 2019)

***Hosta* – Sheffield, United Kingdom**

1）The changes of plant height

In Sheffield, there were significant differences in the changes of *Hosta*'s height only in the first phase ($p < 0.05$) (Fig 4.17).

The plants were overall taller in the first phase, and it was the dry and the medium irrigation treatments that significantly exceeded the wet ($p < 0.05$). The wet treatment was the optimal in the second phase, increasing the plant height by a small amount, while the dry and the medium irrigation treatments caused dieback of the plant height.

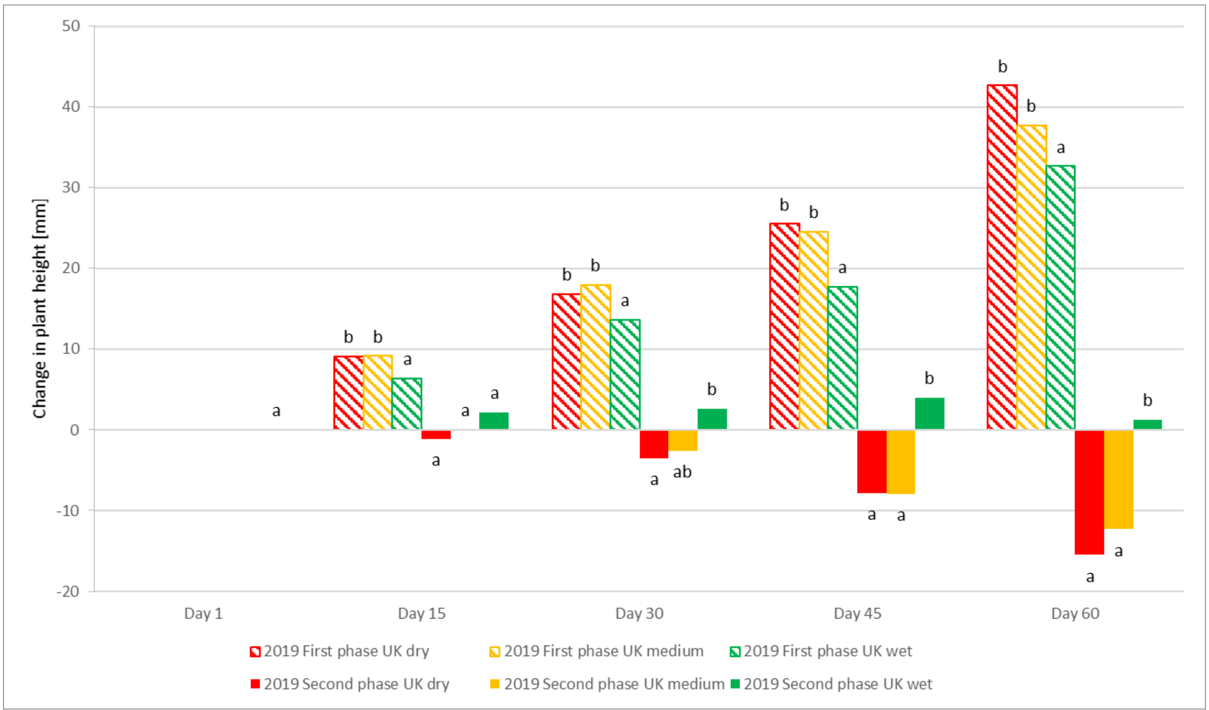

Figure 4.17 The mean change in plant height of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread

The plant spread was dramatically greater in the first phase than in the second phase (Fig 4.18). The dry and the medium treatments had exceeded the wet irrigation treatment, by the end of Day 60 ($p < 0.05$) in the first phase. In contrast, under the wet irrigation treatment the plant spread increased to a significant larger extent than under other treatments ($p < 0.05$).

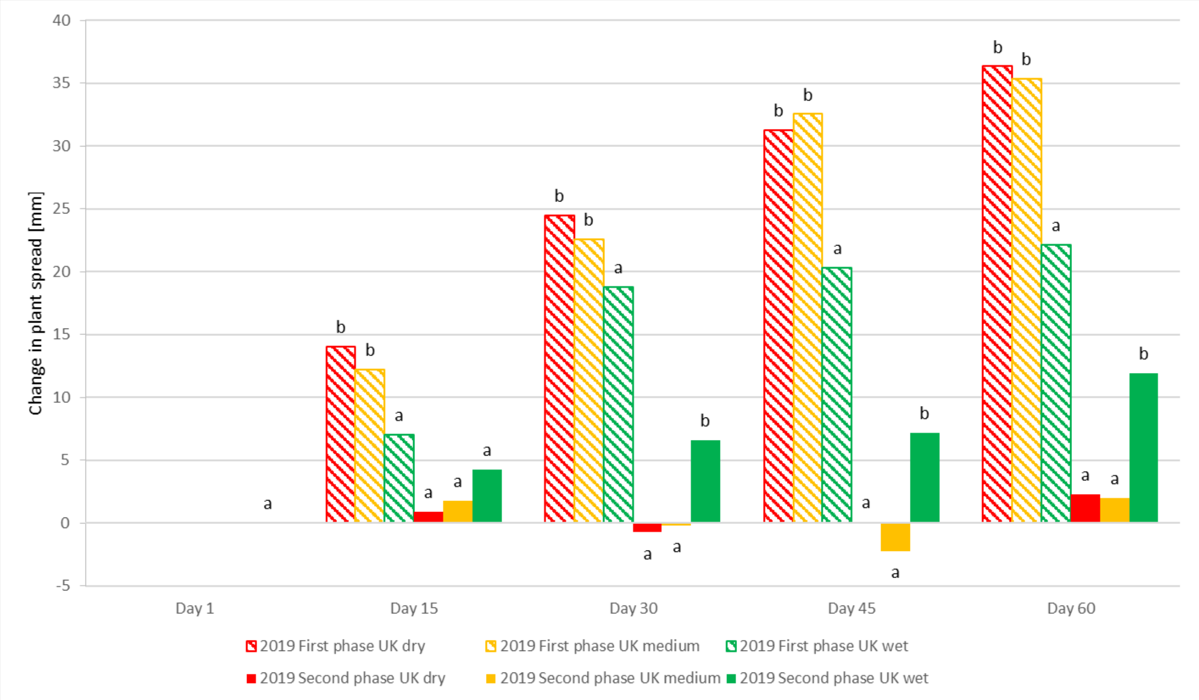

Figure 4.18 The mean change in plant spread of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

The number of the plant leaves newly developed was significantly larger in the first phase (Fig 4.19). However, no treatment difference was evidently caused by water supply by the end of both phases ($p > 0.05$). The increase of leave numbers under dry treatment during the second phase corresponded with a great number of large leaves (1.15 per plant, Table 4.6) compared to other treatments at this time.

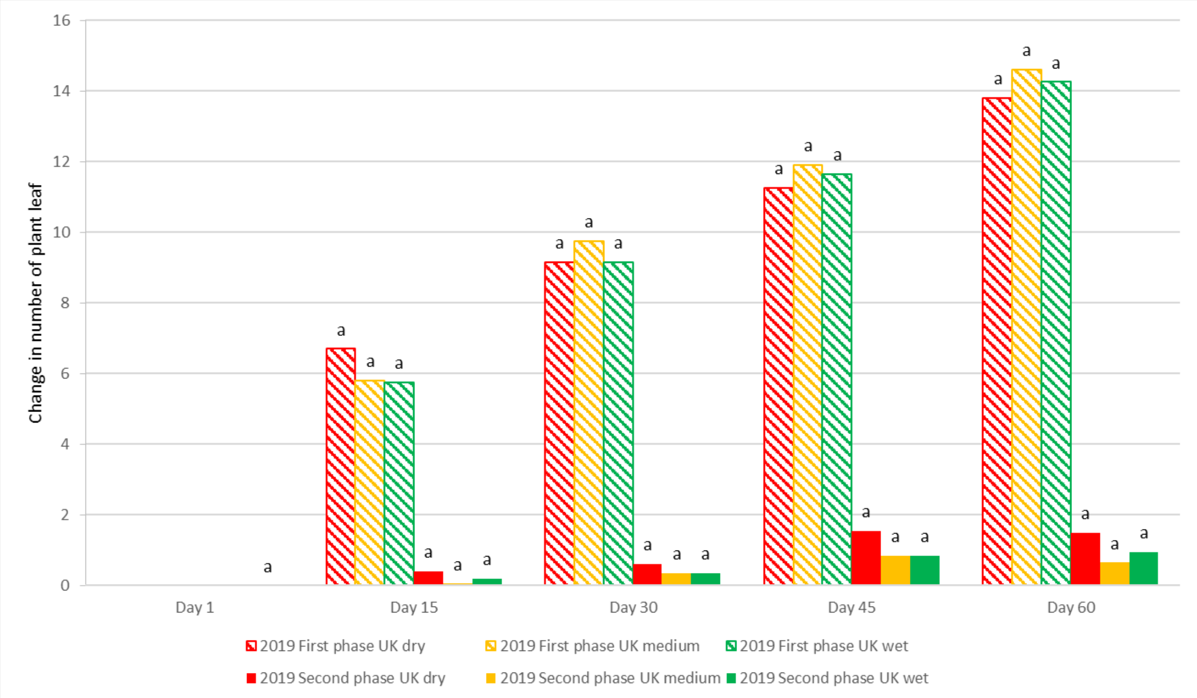

Figure 4.19 The mean change in number of plant leaves of the plant leaves of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

Table 4.6 The mean change in numbers of different size of plant leaves of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2019 First phase CN dry	13.80	1.48	3.70	0.71	1.20	0.61	8.90	0.81
2019 First phase CN medium	14.60	0.99	4.70	0.90	1.00	0.47	8.90	0.65
2019 First phase CN wet	14.25	0.95	5.70	0.74	-0.20	0.73	8.75	0.66
2019 Second phase CN dry	1.50	0.51	1.15	0.49	0.30	0.19	0.05	0.14
2019 Second phase CN medium	0.65	0.42	-0.65	0.41	1.05	0.41	0.25	0.12
2019 Second phase CN wet	0.95	0.48	0.70	0.42	0.30	0.29	-0.05	0.17

4） The changes of plant aesthetic ratings

The plant quality was considerably higher in the first than the second phase of the summer experiments (Fig 4.20). The dry and the medium irrigation treatments optimised the plant quality in the second phase ($p < 0.05$), but there was no difference among treatments in the plant quality in the first phase ($p > 0.05$). Fig 4.21, the changes of the absolute value of the plant aesthetic rating, also verifies this result. There is no significant difference in treatment under different phases, and the average absolute value of the plant aesthetic rating are all around 4.3.

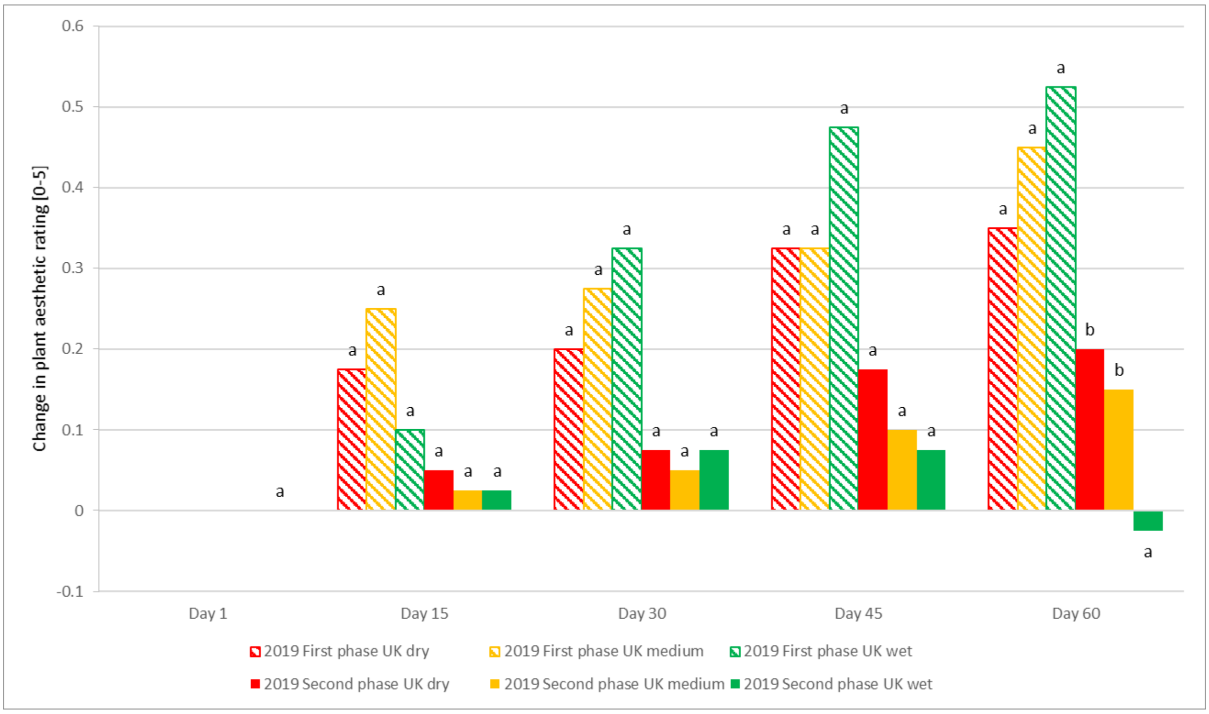

Figure 4.20 The mean change in plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. The letters on the graph denote difference from the transformed values)

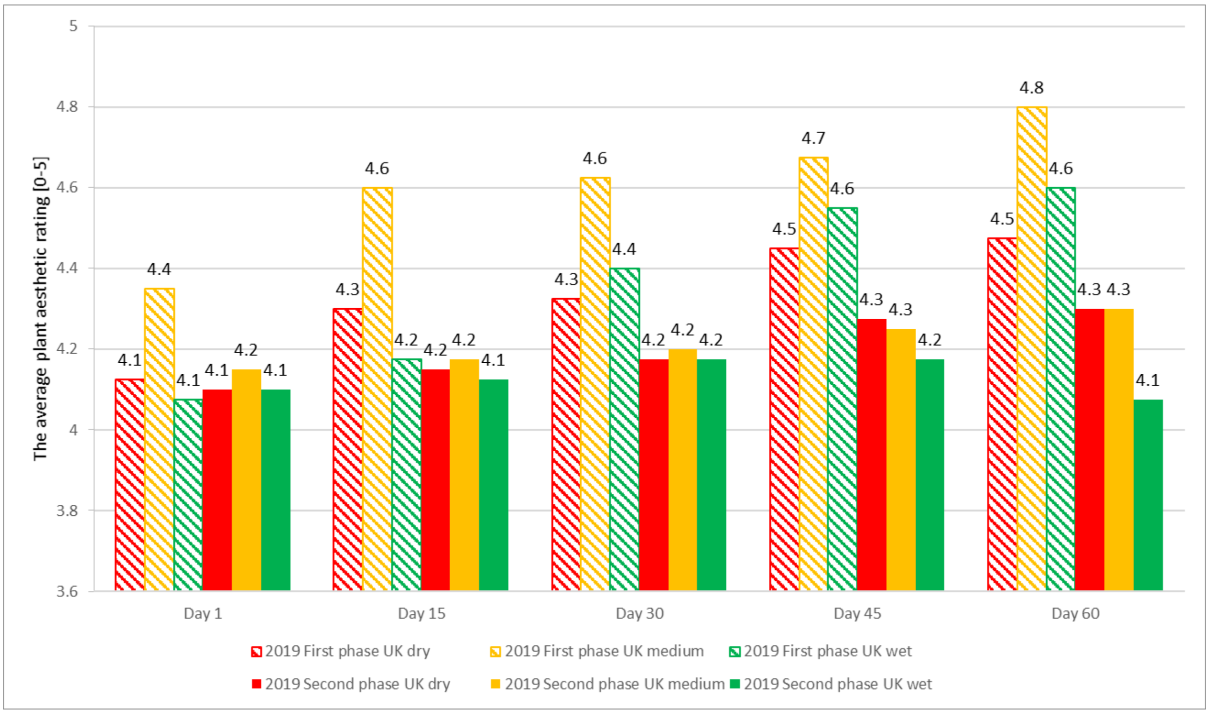

Figure 4.21 The mean value of plant aesthetic rating of *Hosta* 'Blue Mouse Ears' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019)

4.2.3 *Heuchera* 'Marmalade'

***Heuchera* – Jingmen, China**

1）The changes of plant height

In Jingmen, there was a significant difference in the changes of *Heuchera*'s height in both phases ($p < 0.05$) (Fig 4.22).

Overall, the plants grew higher in the first phase, and the optimum treatment at this time was the dry irrigation treatment which significantly exceeded the medium and the wet irrigation treatments ($p < 0.05$). During the second phase, however, the dieback appeared under all treatments and the dry irrigation treatment leaded to a slightly less loss of height than the others ($p > 0.05$).

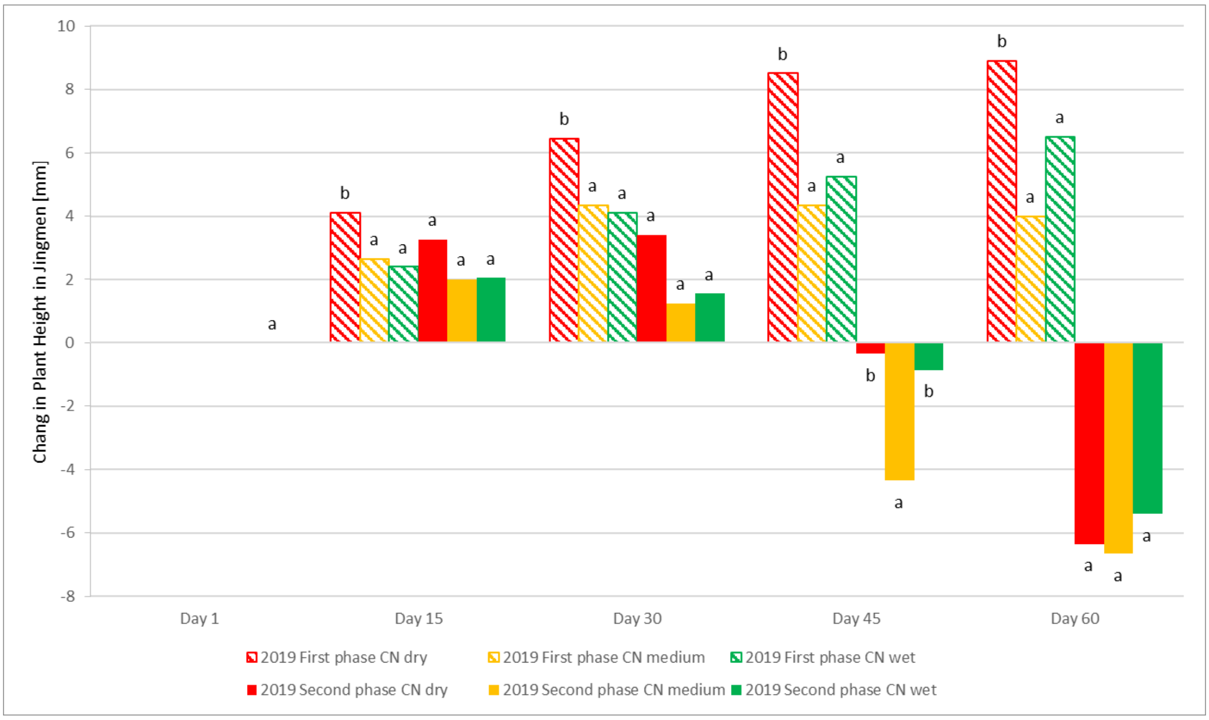

Figure 4.22 The mean change in plant height of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread

The plant spread was generally greater in the early phase (Fig 4.23), when the dry and the wet irrigation treatments had exceeded the medium treamtent ($p < 0.05$). During the second phase, under the wet irrigation treatment the plant spread decreased by a smaller scale than under the medium and the dry treatments ($p < 0.05$). The dieback was evident in all treatments in the Phase 2.

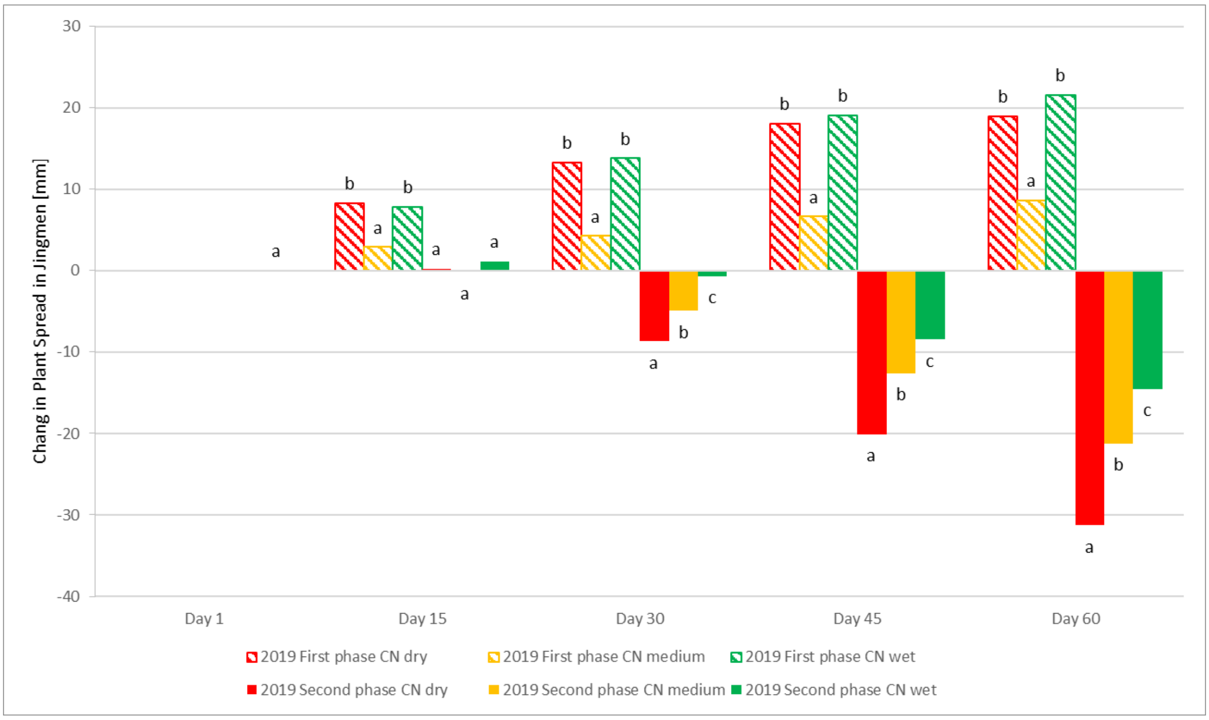

Figure 4.23 The mean change in plant spread of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

Generally, the plants developed a greater number of leaves in the first phase (Fig 4.24), while a significantly increased number of leaves were present on the plants under the medium irrigation treatment by the end of the first phase ($p < 0.05$). This result also corresponded with a great number of large leaves (27.20 per plant) compared to other treatments at this time. During the second phase, the overall leaf number was optimised under the dry irrigation treatment ($p < 0.05$), and this result corresponded with a big number of both large (3.45 per plant) and medium (3.45 per plant, Table 4.7) leaves compared with other treatments.

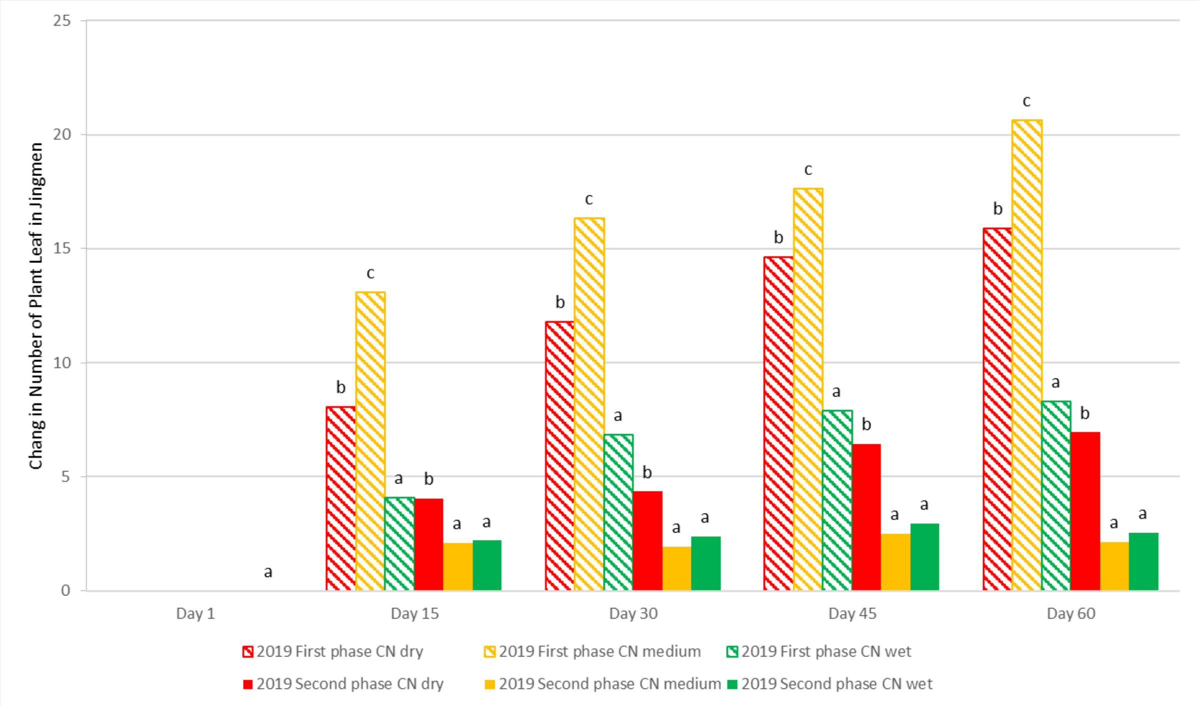

Figure 4.24 The mean change in number of the plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen City, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

Table 4.7 The mean change in numbers of different size of plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in the Jingmen, China (Exp2. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2019 First phase CN dry	15.90	1.67	25.15	2.29	-8.40	2.30	-0.85	0.43
2019 First phase CN medium	20.65	2.24	27.20	2.33	-6.35	2.11	-0.20	0.63
2019 First phase CN wet	8.30	2.40	17.75	1.35	-8.45	2.46	-1.00	0.58
2019 Second phase CN dry	6.95	1.38	3.45	1.02	3.45	1.37	0.05	0.50
2019 Second phase CN medium	2.15	0.97	0.90	0.87	1.40	0.96	-0.15	0.39
2019 Second phase CN wet	2.55	0.95	2.25	0.89	-0.05	1.04	0.35	0.65

4） The changes of plant aesthetic ratings

The plant quality was considerably high both in the first and the second phase of the summer experiments (Fig 4.25). The medium irrigation treatment optimised the plant quality in the first phase, but there was no difference of the plant quality among different irrigation treatments in the second phase. Fig 4.26 shows that the actual aesthetic ratings are all relatively high, with an average value of about 4.5 in both phases and treatments.

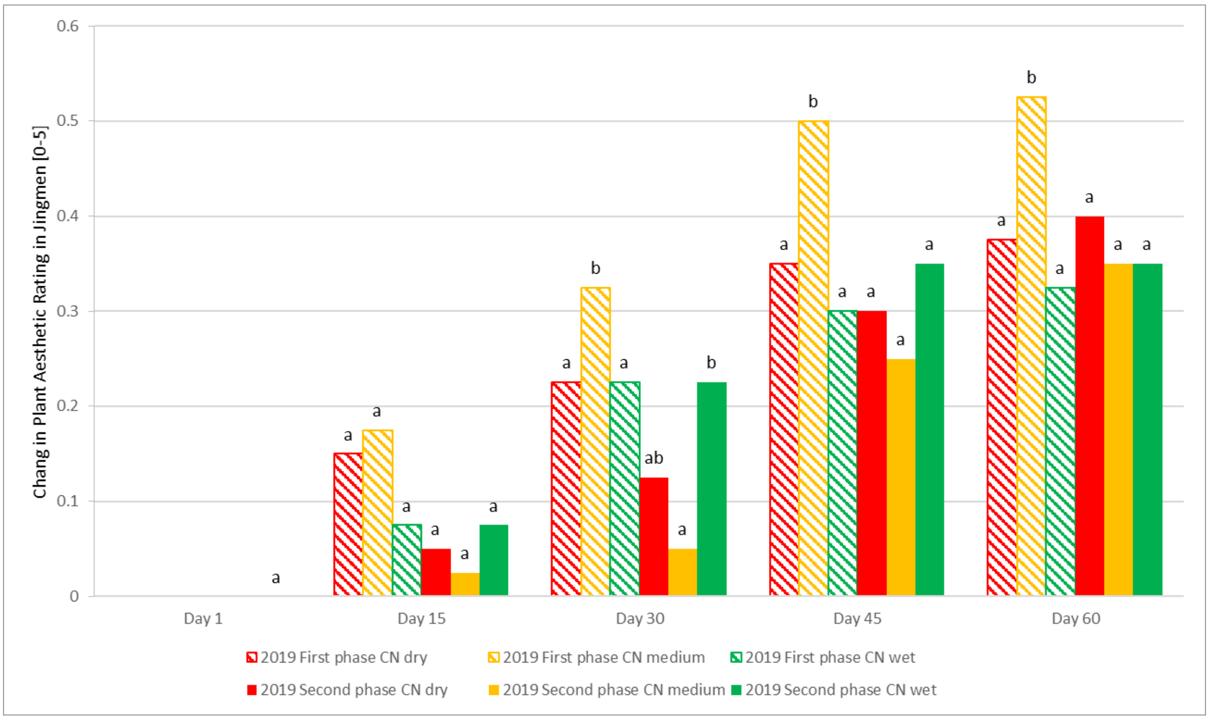

Figure 4.25 The mean change in plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen City, China (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

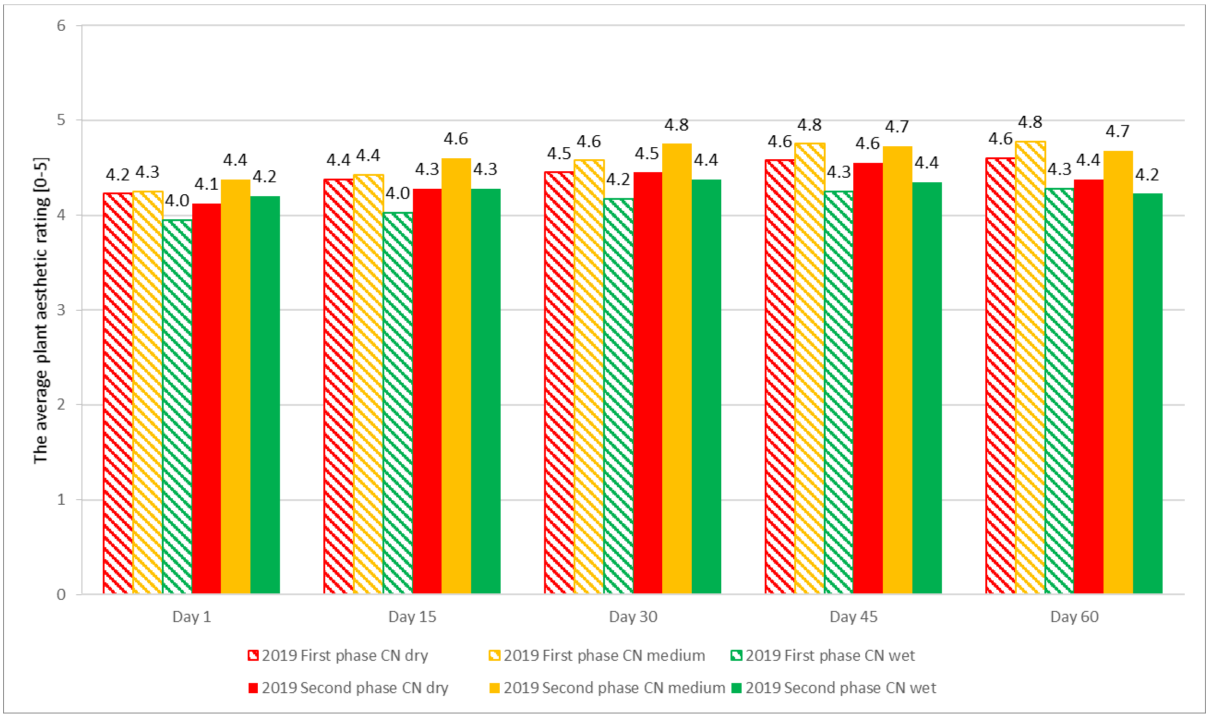

Figure 4.26 The mean value of plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Jingmen City, China (Exp2. in 2019)

***Heuchera* – Sheffield, United Kingdom**

1) The changes of plant height

In Sheffield, there were significant differences in the changes of *Heuchera's* height in both phases ($p < 0.05$) (Fig 4.27).

The growth of the plants was overall better in the first phase (Fig 4.27), and the optimum treatment at this time was the wet irrigation treatment which significantly exceeded the dry and the medium treatments ($p < 0.05$). However, in the second phase, the plant growth under the dry treatment was significantly greater than that under the medium and the wet treatments ($p < 0.05$).

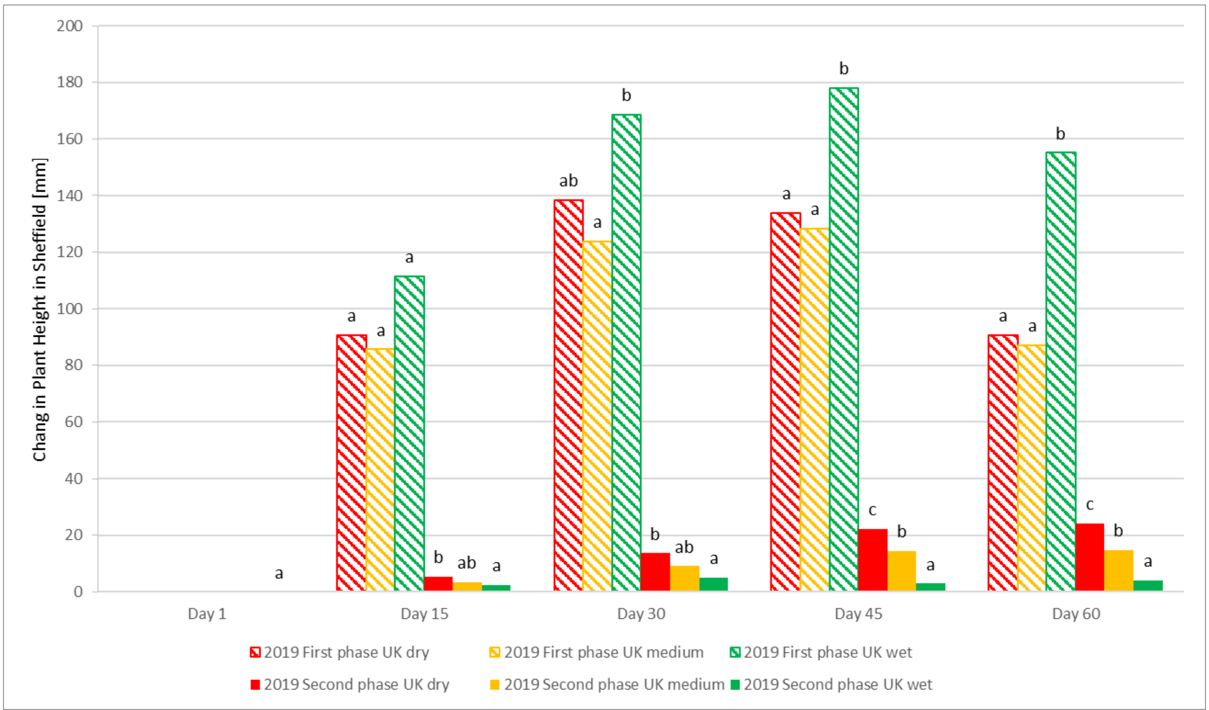

Figure 4.27 The mean change in plant height of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

2) The changes of plant spread

There is no significant difference in the plant spread changes in both phases (Fig 4.28). During the first phase, the plant spread significantly increased under the wet irrigation treatment compared to the medium and the dry treatments ($p < 0.05$), by the end of Day 60. By contrast, the plant spread under the medium and the dry treatments increased more than under the wet treatment in the second phase ($p < 0.05$).

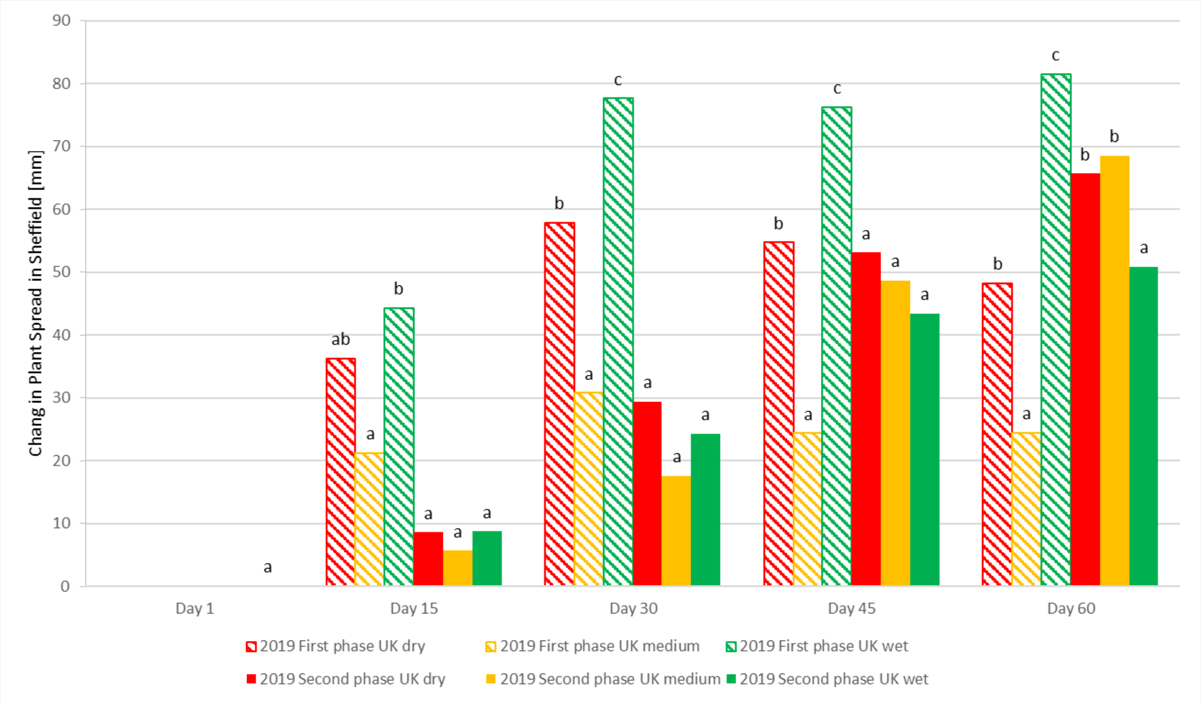

Figure 4.28 The mean change in plant spread of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

3) The changes of numbers of plant leaves

In general, the plants developed a slightly greater number of leaves in the second phase (Fig 4.29), while an increased number of leaves were present on the plants under the dry irrigation treatment by the end of first phase ($p < 0.05$). This treatment during the second phase also resulted a huge number of large leaves (37.80 per plant) compared to other treatments. During the first phase, the overall leaf number was optimised under the dry and the wet irrigation treatments ($p < 0.05$). Nevertheless, the dry treatment during this phase facilitated the increase of medium leaves (25.55 per plant) while the wet treatment during this phase promoted the number of large leaves (32.50 per plant, Table 4.8).

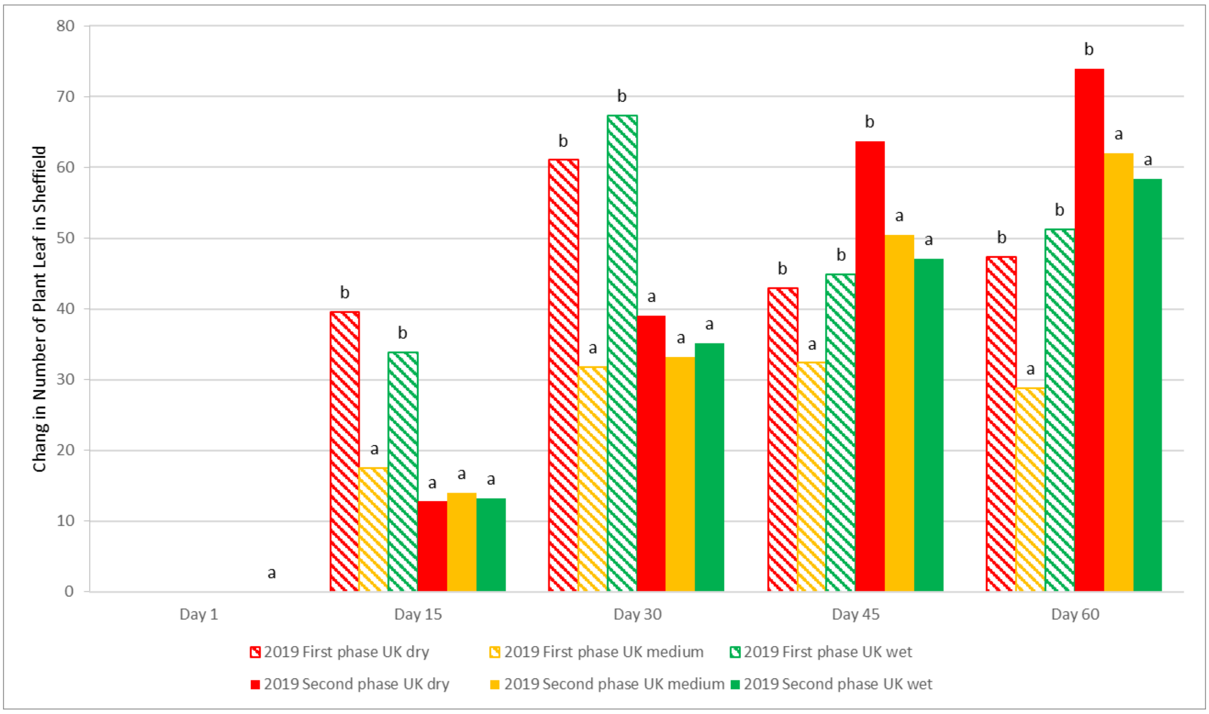

Figure 4.29 The mean change in number of the plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

Table 4.8 The mean change in numbers of different size of plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
2019 First phase CN dry	47.40	4.86	20.60	2.62	25.55	3.44	1.25	1.31
2019 First phase CN medium	28.80	3.81	22.20	2.66	6.80	1.49	-0.20	1.19
2019 First phase CN wet	51.30	2.72	32.50	2.69	16.45	1.65	2.35	1.15
2019 Second phase CN dry	74.00	4.62	37.80	3.59	29.95	3.37	6.25	0.69
2019 Second phase CN medium	62.05	4.36	34.40	2.93	24.00	3.68	3.65	0.73
2019 Second phase CN wet	58.40	3.01	32.85	2.81	21.45	2.49	4.10	0.49

4) The changes of plant aesthetic ratings

The plant quality was considerably high both in the first and the second phase of the summer experiments (Fig 4.30). The wet irrigation treatment optimised the plant quality in the first phase while the dry treatment optimised the plant quality in the second phase ($p < 0.05$). Fig 4.31 also shows that the absolute value of aesthetic rating in the first phase is slightly greater than that in the second phase. This corresponds with the trend of the optimal irrigation treatment that the wet treatment in the first phase and the dry treatment in the second is relatively better.

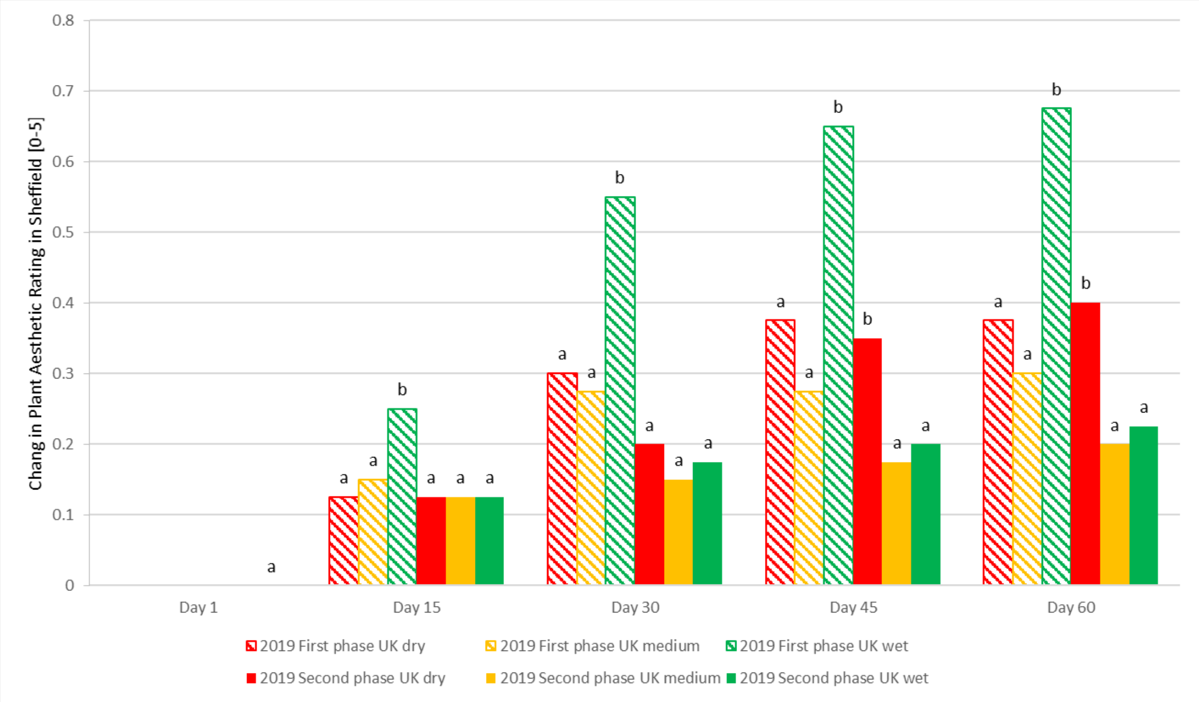

Figure 4.30 The mean change in plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

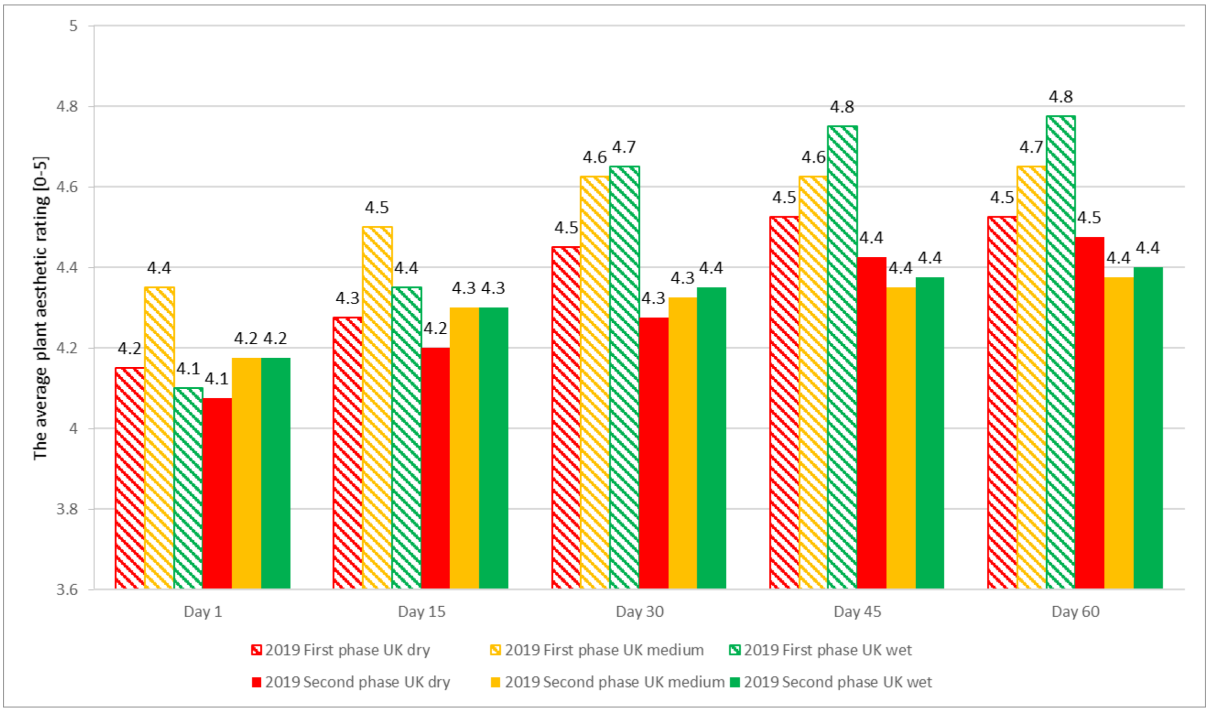

Figure 4.31 The mean value of plant aesthetic rating of *Heuchera* 'Marmalade' under different irrigation treatments in Sheffield, United Kingdom (Exp2. in 2019)

4.2.4 Correlation Between Meteorological Factors and Plant Growth

4.2.4.1 Change in meteorological factors

Overall, the average daily air temperature of Jingmen in 2019 is higher than that of Sheffield in the same phase (difference is approximately 10 °C) (Fig 4.32). The curves of temperature in the two cities were similar, both fluctuating more in the first phase and relatively stable in the second phase. The records of highest average daily air temperature were reached in the second phase in both cities, which is the 31.9 °C on 20 Aug 2019 in Jingmen and 26.1 °C on 25 Jul 2019 in Sheffield. The lowest temperature that appeared in two cities were the 14.8°C on 07 Jun 2019 in Jingmen and 6.4°C on 03 Jun 2019 in Sheffield.

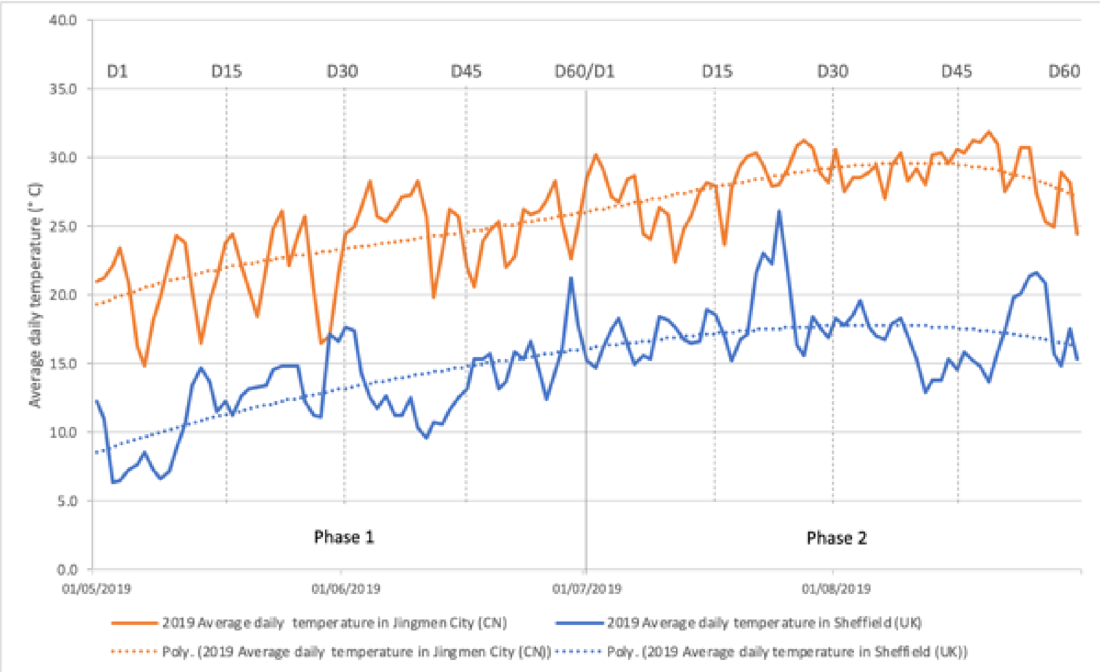

Figure 4.32 Average daily air temperature 2 metres above the ground in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp2. in 2019)

On the other hand, the average daily relative humidity in Sheffield (average approx. 91%) is higher than that in Jingmen (average approx. 74%) (Fig 4.33). The changes of relative humidity in Sheffield are relatively stable, and there is little difference between the change during the first phase (average approx. 91%) and the second phase (average approx. 90%). However, the average daily relative humidity in Jingmen shows that the humidity in early part of phase 1 and later part in phase 2 are at a low level (approx. 70%), while the mean value of the relative humidity in the rest of two phases are close to 80%. The highest record of relative humidity in the Sheffield was the 100% on 13 Jun, 24 Jun and 26 Jun 2019; the highest record in the Jingmen was 97% on 17 Jun 2019. The lowest point is 75% on 30 Jun 2019 in the Sheffield and is 45% on 02 Jun and 20 Jun 2019 in the Jingmen.

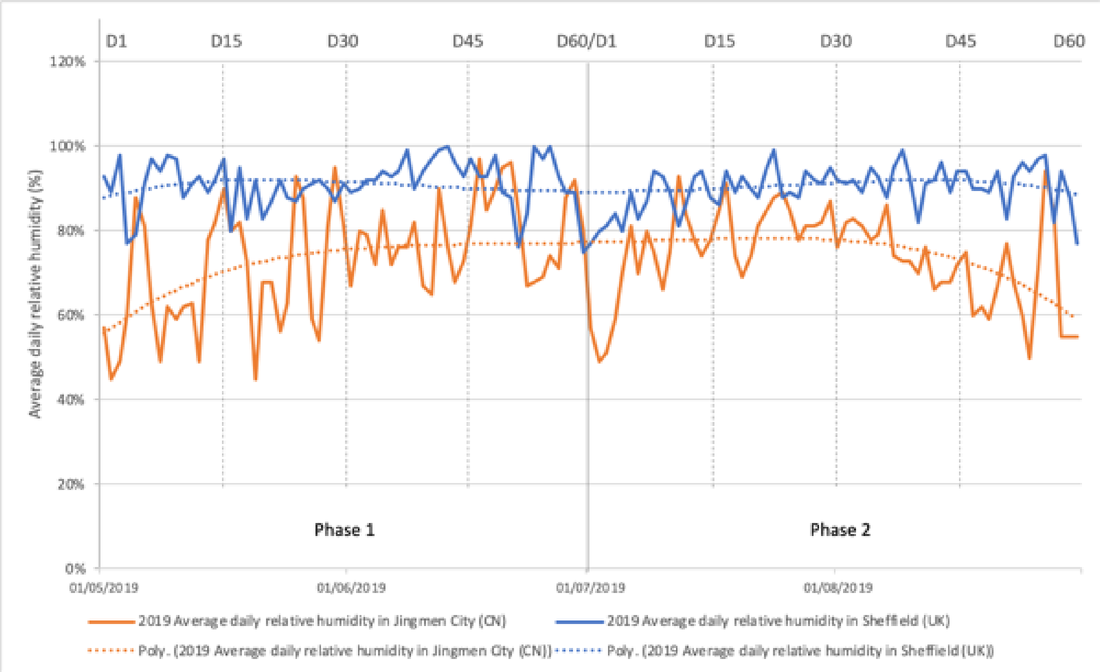

Figure 4.33 Average daily relative humidity 2 metres above the ground in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp2. in 2019)

The total amount of precipitation during the 2 phases in Jingmen (approx. 518 mm) was greater than that in Sheffield (approx. 347 mm), while the frequency of rainfall in Sheffield (64 times rain records) was greater than that in Jingmen (39 times rain records) (Fig 4.34). In Jingmen, both the maximum precipitation records and the highest frequency of precipitation occurred in the first phase, in which there were 4 times of rainfall over 20mm per day, and the maximum rainfall was on20 Jun 2019 with a total of 95.8 mm in that day. In Sheffield, however, the highest rainfall occurred in the second phase. There were four occasions of the rainfall over 20 mm in that phase. The maximum rainfall was 25 mm on 28 Jul 2019.

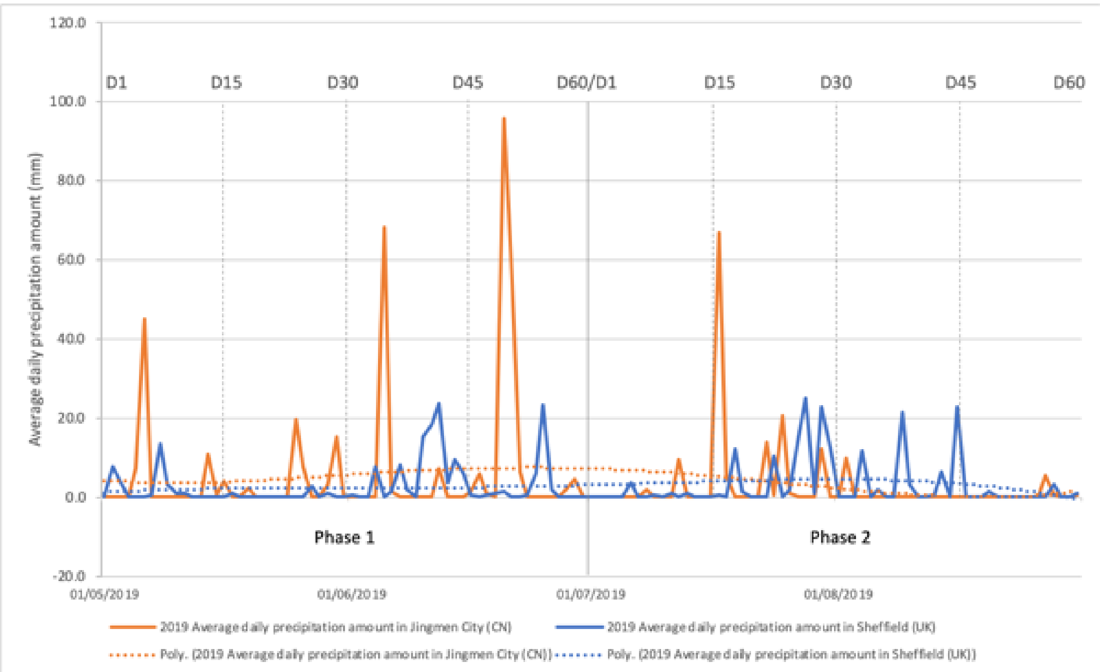

Figure 4.34 Average daily precipitation amount in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp2. in 2019)

The curve of changes in air pressure (Fig 4.35) shows that the average air pressure in Jingmen was slightly lower than that in Sheffield but was relatively more stable. There was little difference of pressure changes between the two cities in the first and second phases. The average pressure in the Sheffield was 1014.2 hPa and that in Jingmen was 983.9 hPa. The highest points of pressure records were 1035.2 hPa on 13 Jun 2019 in Sheffield and 994.9 hPa on 06 Jun 2019. The lowest points, however, were 995.6 hPa on 09 Jun and 10 Aug 2019 in Sheffield and 976.2 hPa on 28 Jun 2019 at Jingmen.

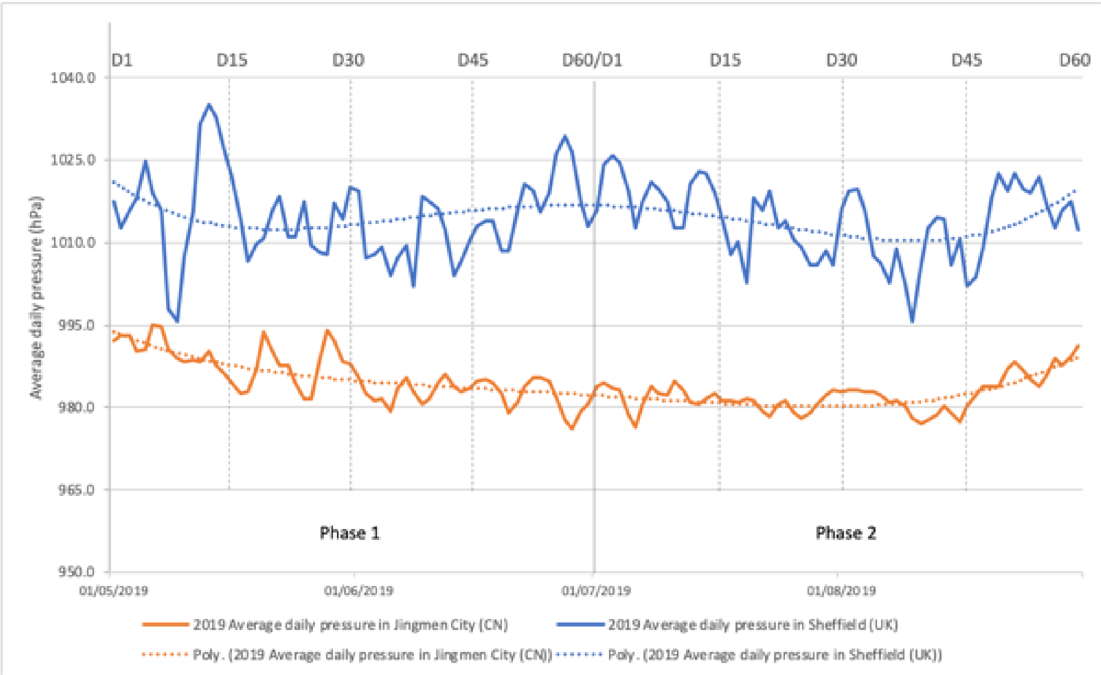

Figure 4.35 Average daily pressure in Jingmen, China (Orange) and Sheffield, the United Kingdom (Blue) (Exp2. in 2019)

4.2.4.2 *Vinca major* 'Variegata'

Correlating plant parameters to weather parameters shows that plant growth is mainly related to temperature and relative humidity (Table 4.9). There is a generally negative moderate linear correlation (r = -0.40 to -0.59) between the growth and the temperature and a generally positive strong linear correlation (r = 0.60 to 0.79) between the growth and the relative humidity. Specifically, the strongest correlations between the growth and the relative humidity are showed by the number of plant leaves under the dry (r = 0.751), the medium (r = 0.758), and the wet (0.735) treatments respectively. Furthermore, the strongest correlations between the growth and the pressure are showed by the number of plant leaves under the dry (r=0.714), the medium(r=0.701), and the wet(r=0.654) treatments. The number of the leaves also has a positive strong liner correlation with the pressure under all treatments but a negative strong liner correlation with the temperature under the dry (-0.637) and the medium (-0.630) treatment.

Table 4.9 The correlation analysis between meteorological factors and *Vinca major* 'Variegata' growth (Exp2. in 2019)

IRRIGATION TREATMENT	PLANT INDEX	TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]
Dry	Plant height	-0.581*	0.602*	0.180	0.504*
	Plant spread	-0.426	0.622*	-0.033	0.535*
	Plant leaves	-0.637**	0.751**	-0.015	0.714**
Medium	Plant height	-0.291	0.300	0.472	0.108
	Plant spread	-0.568*	0.619*	0.076	0.543*
	Plant leaves	-0.630**	0.758**	0.009	0.701**
Wet	Plant height	-0.367	0.395	0.267	0.256
	Plant spread	-0.435	0.485	0.168	0.352
	Plant leaves	-0.558*	0.735**	-0.007	0.654**

**. The correlation is significant at the significance level of 0.01 (2-tailed).
*. The correlation is significant at the significance level of 0.05 (2-tailed).

4.2.4.3 *Hosta* 'Blue Mouse Ears'

Plant growth is mainly related to the temperature and the relative humidity (Table 4.10). There is a generally negative strong linear correlation (r = -0.60 to -0.79) between the growth and the temperature and a generally positive moderate linear correlation (r = 0.40 to 0.59) between the growth and the relative humidity. Specifically, the strongest correlations between the growth and the temperature are showed by the plant spread under the dry (r = -0.743), the medium (r = -0.672), the wet (r = -0.794) treatment. The number of the plant leaves under dry (r = -0.608), wet (r = -0.614) treatments also counts in the correlation. Also, the plant spread has a moderate positive liner correlation with the relative humidity and the pressure under the dry and the medium treatments and a strong positive liner correlation under the wet treatment.

Table 4.10 The correlation analysis between meteorological factors and *Hosta* 'Blue Mouse Ears' growth (Exp2. in 2019)

IRRIGATION TREATMENT	PLANT INDEX	TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]
Dry	Plant height	-0.287	0.170	0.097	0.149
	Plant spread	-0.743**	0.576*	0.042	0.565*
	Plant leaves	-0.608*	0.488	0.000	0.470
Medium	Plant height	-0.379	0.259	0.035	0.256
	Plant spread	-0.672**	0.519*	0.009	0.507*
	Plant leaves	-0.580*	0.444	0.026	0.437
Wet	Plant height	-0.567*	0.450	0.144	0.453
	Plant spread	-0.794**	0.645**	0.039	0.647**
	Plant leaves	-0.614*	0.482	0.059	0.464

**. The correlation is significant at the significance level of 0.01 (2-tailed).
*. The correlation is significant at the significance level of 0.05 (2-tailed).

4.2.4.4 *Heuchera* 'Marmalade'

plant growth is mainly related to the temperature and the relative humidity (Table 4.11). There is a generally negative strong linear correlation (r = -0.60 to -0.79) between the growth and the temperature and a generally positive strong linear correlation (r = 0.60 to 0.79) between the growth and the relative humidity. Specifically, the strongest correlations are between the plant leaves number and the temperature (r = 0.802) and between the plant leaves number and the pressure (r = 0.822) under the wet treatment, and between the plant spread and the temperature under the dry treatment (r = -0.818).

Table 4.11 The correlation analysis between meteorological factors and *Heuchera* 'Marmalade' growth (Exp2. in 2019)

IRRIGATION TREATMENT	PLANT INDEX	TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]
Dry	Plant height	-0.764*	0.621*	-0.096	0.614*
	Plant spread	-0.818**	0.738**	0.105	0.721**
	Plant leaves	-0.734**	0.782**	-0.135	0.777**
Medium	Plant height	-0.758**	0.603*	-0.093	0.604*
	Plant spread	-0.686**	0.712**	0.057	0.673**
	Plant leaves	-0.617*	0.693**	0.046	0.666**
Wet	Plant height	-0.700**	0.552*	-0.094	0.559*
	Plant spread	-0.795**	0.769**	0.053	0.704**
	Plant leaves	-0.786**	0.802**	-0.177	0.822**

**. The correlation is significant at the significance level of 0.01 (2-tailed).
*. The correlation is significant at the significance level of 0.05 (2-tailed).

4.2.4.5 The correlation between plant aesthetic rating and other factors

The plant aesthetic ratings of all plant species were mainly related to the plant physical indexes (the plant height, spread, leaves) (Table 4.12). The plant aesthetic ratings of *Vinca* are mainly correlated with the plant physical indexes under the medium treatment, while those of *Hosta* and *Heuchera* are mainly correlated with the plant physical indexes under the wet treatment. Moreover, the strongest correlation is found between the aesthetic ratings of *Vinca* and the plant spread under the medium treatment (0.831).

Table 4.12 The correlation analysis between the plant growth and the plant aesthetic ratings and between the meteorological factors and the plant aesthetic ratings (Exp2. in 2019)

		TEMPERATURE [2 M]	RELATIVE HUMIDITY [2 M]	PRECIPITATION AMOUNT [MM]	PRESSURE [MEAN SEA LEVEL]	Plant Height	Plant Spread	Plant leaves
Plant aesthetic rating - *Vinca major* 'Variegata'	Dry	-0.421*	0.507**	0.009	0.438*	0.627**	0.678**	0.799**
	Medium	-0.390*	0.424*	0.068	0.271	0.695**	0.831**	0.678**
	Wet	0.390*	-0.136	0.051	-0.407*	0.339	0.356	0.034
	Dry	0.239	-0.068	0.188	-0.359	0.359	0.205	0.376*

Plant aesthetic rating - *Hosta* 'Blue Mouse Ears'	Medium	0.177	0.025	0.059	-0.312	0.430*	0.279	0.376*
	Wet	-0.034	0.017	0.376*	-0.188	0.592**	0.376*	0.479*
Plant aesthetic rating - *Heuchera* 'Marmalade'	Dry	-0.009	0.182	-0.009	0.043	0.234	0.303	0.390*
	Medium	0.093	-0.076	0.059	-0.177	0.102	0.059	0.127
	Wet	-0.060	0.179	-0.060	0.026	0.400*	0.366	0.247

**. The correlation is significant at the significance level of 0.01 (2-tailed).
*. The correlation is significant at the significance level of 0.05 (2-tailed).

4.2.5 Results Overview for Exp 2

Comparing the data of different plant species across both countries, it can be seen that *Vinca* is the species that during the first phase, with UK plants particularly growing long, wide and having plenty of leaves (Figs 4.36 to 4.39). Extension growth in this species (Fig 4.36) and spread (Fig 4.37) was greater in first phase compared to second phase in both UK and China. The plant height was significantly increased in the first phase (avg. 108 mm) compared with the second phase (avg. 42 mm). *Heuchera* was another species that grew well in first phase, but only in the UK (Fig 4.36). The wetter regime being an advantage here, with growth (Figs 4.36 and 4.37) and quality (Fig 4.39) being superior in this treatment. The dieback of this species was shown in the plant height (Fig. 4.36) and spread (Fig. 4.37) in second phase of CN under all irrigation treatments. Growth in *Hosta* was less than the other two species, but was still preferentially favoured during Phase 1 conditions in the UK.

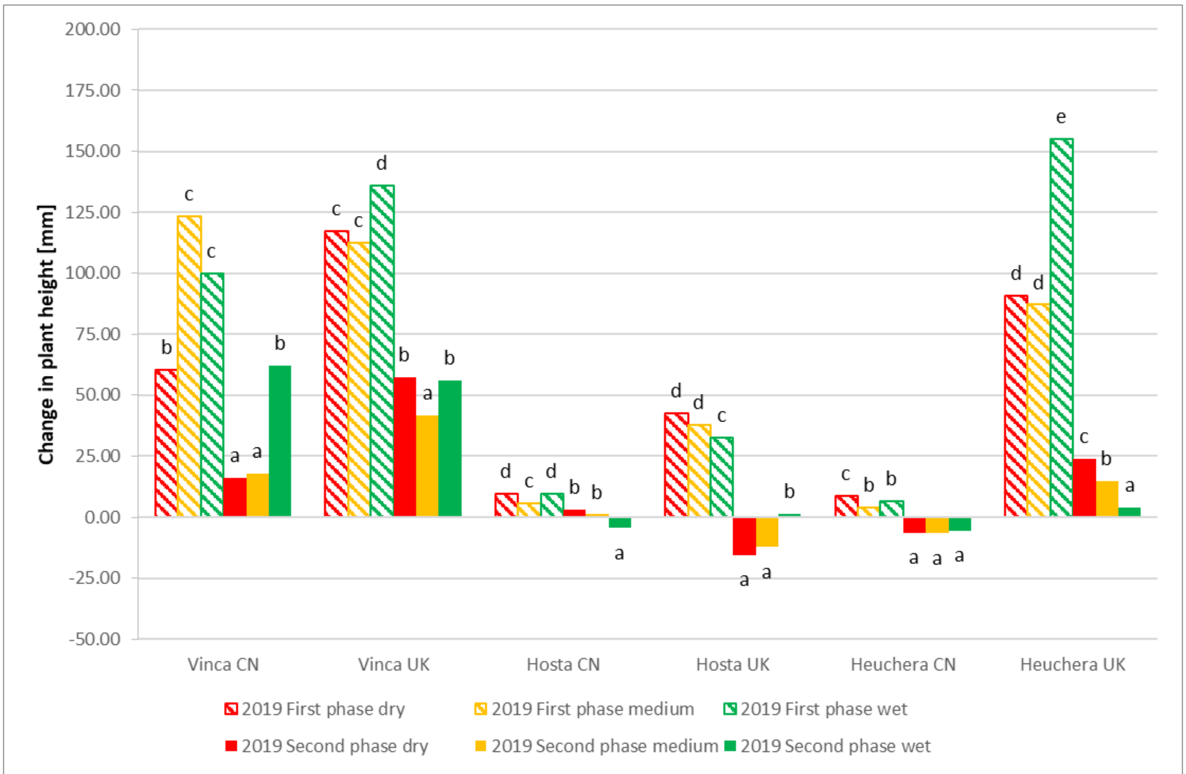

Figure 4.36 The mean change of plant height in Day 60 (three species in two cities during 2 phases) (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

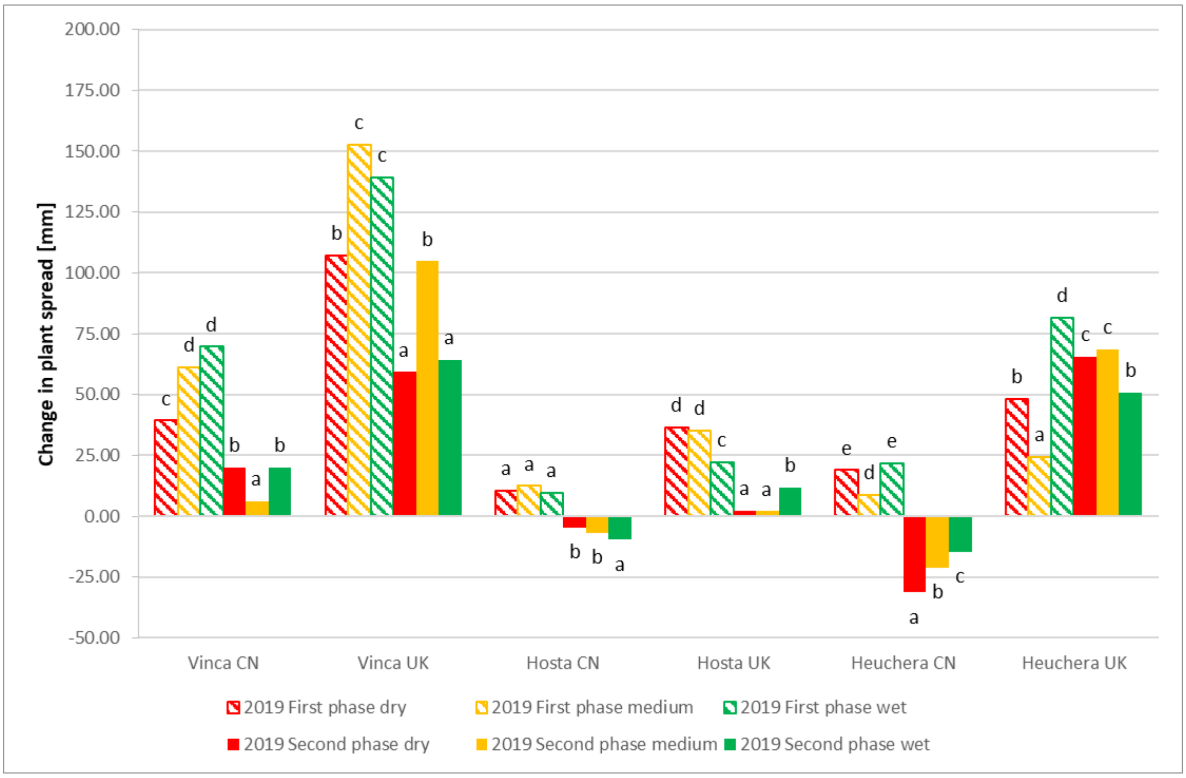

Figure 4.37 The mean change of plant spread in Day 60 (three species in two cities during 2 phases) (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

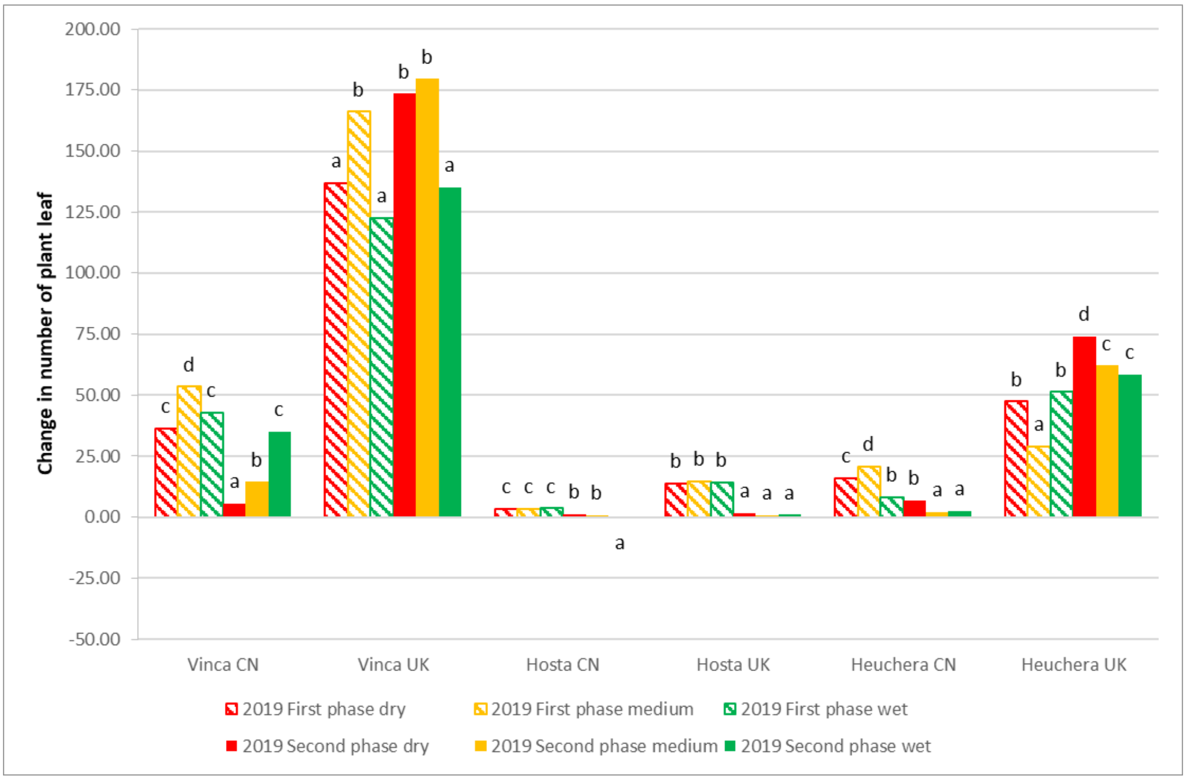

Figure 4.38 The mean change of plant leaf number in Day 60 (three species in two cities during 2 phases) (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

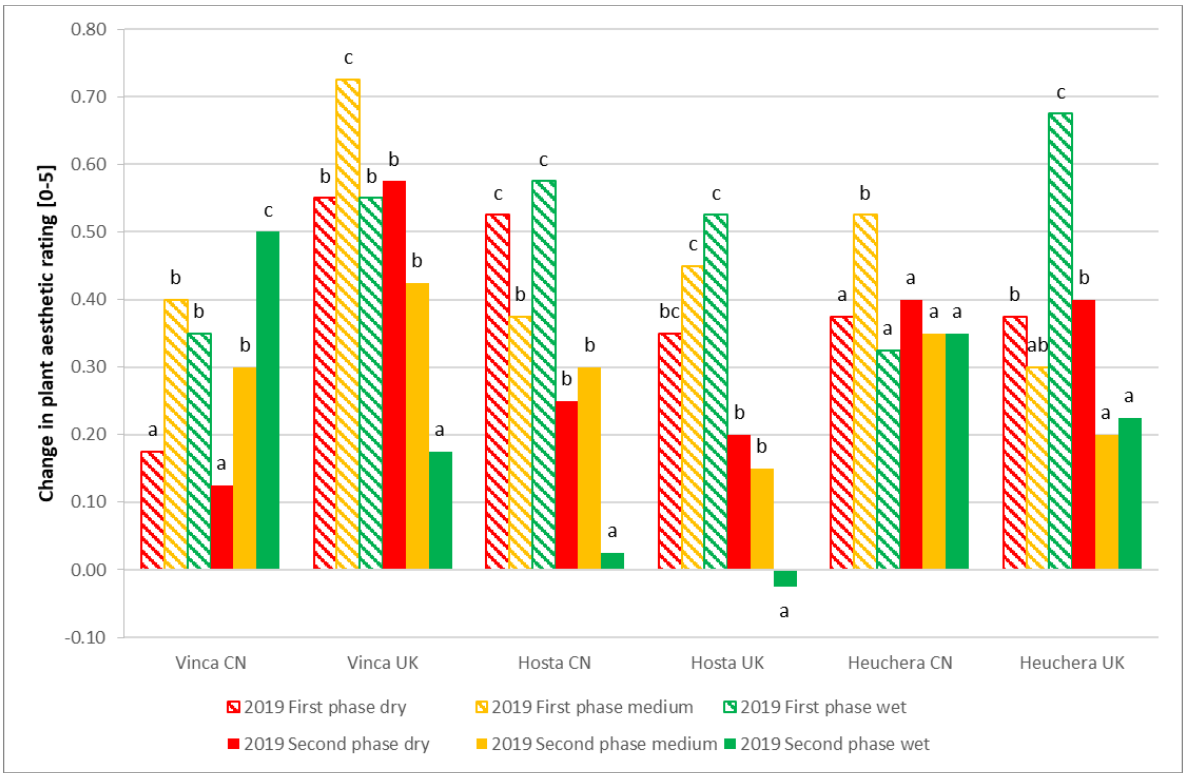

Figure 4.39 The mean change of plant aesthetic rating in Day 60 (three species in two cities during 2 phases) (Exp2. in 2019) (NB. the letters on the graph denote difference from the transformed values)

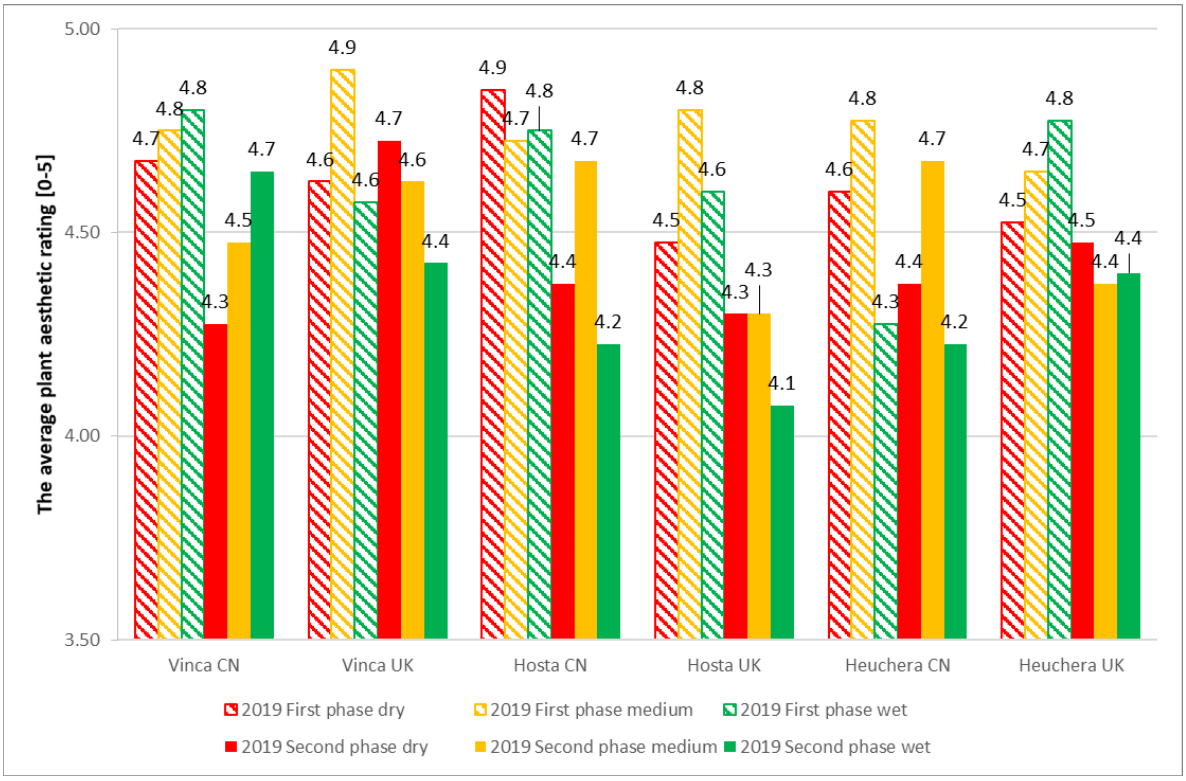

Figure 4.40 The mean value of plant aesthetic rating in Day 60 (three species in two cities during 2 phases) (Exp2. in 2019)

4.3 EXPERIMENT DISCUSSION

4.3.1 Overall Discussion

In general, the three selected experimental plant species have their own distinctive characteristics in the LWS environment. *Vinca* showed the most consistent strongest shoot growth, particularly through the first phase in both Jingmen and Sheffield. *Heuchera* performed well in Sheffield during first phase, but was much less so in the second phase (Fig 4.36). In a number of situations these plants' growth was optimized by the wetter irrigation regimes. *Hosta*, on the other hand, had the slowest growth and even showed dieback in the second phase. *Heuchera* too, performed poorly in the summer (i.e., second phase) in Jingmen. Some trends about the effect on plant growth by different irrigations, location and time could be summarised as follows:

1) Even though the irrigation treatments, location and time all had significant effects on the plant growth performance of the three plant species ($p < 0.05$), the degree of influence of each factor was different for different species. Generally, the most influential factors were the irrigation treatments and time on *Vinca*, irrigation treatments, location and time on *Heuchera*, and the time on the *Hosta*.

2) The plant growth was also closely related to the drought tolerance of plants during the mixed planting scheme in LWS. The experiment 2 generally shows that the higher the drought tolerance of plants, the less the environmental influence on their growth. The *Vinca*, for example, grew better in all indicators than the other two plant species. The growth rate of *Heuchera* is between the *Vinca* and *Hosta* as it is a plant with relatively moderate drought tolerance. However, plant growth rate is also limited by the plant's biological characteristics (e.g., maximum plant height).

3) Although there is no dead plant during the two-month phase experiment in Exp 2, the dead signals shown on the table of plant growth recording that some negative growth in plants size from last day (day 60) compared to their initial size (day 1).

4.3.2 Plant Species

4.3.2.1 *Vinca major* 'Variegata'

Vinca showed significantly increased growth compared to the other two plant species in LWS mixed planting scheme. Both the irrigation treatments and the climate can have an impact on the growth of *Vinca*. *Vinca* becomes more sensitive to climatic factors – particularly temperature as moisture levels in the growth medium become more limited – see Phase 3 in China (Fig 4.36). Therefore, moist growth media strengthens *Vinca's* ability to resist climate changes. This point is re-enforced by the correlation data (Table 4.9) again suggesting plants with the wettest growing media, were least affected by high temperature. Among the four climate factors affecting plant growth, the temperature is the only factor that restrains plant growth. Plant growth drops to its lowest level when the temperature is above average daily at

35°C. The growth of plants increases with the increase of pressure and relative humidity especially for the plants under the dry and the medium treatments. Although, direct comparisons between Exp 1 and 2 are difficult, there was no evidence that *Vinca* was adversely affected by being in the same planter as the other two species, at least when water was not limited.

As discussed the aim of a LWS may not be to optimize growth, but keep growth slow and regular (less pruning required), whilst optimizing plant quality (aesthetics). *Vinca* in the UK was relatively consistent in quality terms (Fig 4.11), although the medium irrigation treatment was the best in terms of improving the aesthetics (Fig 4.10). In China, aesthetics tended to be best when plants were on the wet irrigation treatment (Figs 4.5 and 4.6) again suggesting that adequate water was a priority in the hotter summer climate of China, not only for growth, but also for quality.

4.3.2.2 *Hosta* 'Blue Mouse Ears'

For *Hosta*, the overall growth shows a similar trend with other plant species in LWS under the mixed planting scheme. In general, the growth of plants is better in the first phase than in the second phase, and is greater in Sheffield than in Jingmen. Although significant differences were noted statistically among irrigation treatments, they were not large enough to be observed visually. The volume of irrigation supplied in later spring (phase 1) did not optimize growth in the wetter regime in the UK (Figs 4.36 and 4.37). In summer (Phase 2), however, there was some suggestion the wetter regime was reducing the amount of leaf die-back the plants were experiencing (Fig 4.38), however overall quality was not deemed the highest in these plants (Figs 4.20 and 4.21). *Hosta* plants in the UK grew 30-45 mm during Phase 1 (more than they did in Exp 1) suggesting development at this stage was not compromised, although it is possible that the less growth in the wet treatment, may be due to competition (for light or water) from neighbouring *Heuchera* plants that were also growing well at this time (Figs 4.36 and 4.37). During Phase 1, plants in the UK grew more strongly than their Chinese equivalents indicating that high temperatures in China may have been inhibitory to growth.

Growth was limited in *Hosta* compared to the other 2 species; particularly so perhaps as this is a dwarf variety of *Hosta* anyway. Excessive vigour is unlikely to be a problem with this species due to its natural growth characteristics. Aesthetics are still important however, and quality was seen to reduce between early and late summer in both locations, suggesting that leaf quality. Dieback later in summer may be a disadvantage with this species. The reasons for this are not clear and may simply be early natural senesce in late summer / early autumn, as much as any problem associated with temperature, irrigation or competition from other species.

4.3.2.3 *Heuchera* 'Marmalade'

For *Heuchera*, the overall growth in Sheffield was also higher than in Jingmen (Figs 4.36 to 4.38). The difference between plant growth in Jingmen and Sheffield was mostly marked by the plant height change in the first phase. Different soil moisture levels also caused significant differences to plant growth, with wet conditions favouring growth in the UK during Phase 1.

The wet irrigation treatment brought about not only a significant increase in plant size of *Heuchera*, but also an increase of plant leaf number, which together led to the significantly highest aesthetical rating compared with other treatments (Fig 4.39). Growth of *Heuchera* seemed strongly influenced by climate, with the latter period of summer in China causing cessation of growth or even some dieback, irrespective of irrigation supplied. The correlation between the plant growth and the climate factors are higher than other plants (Table 4.13). It provides further support that the growth of *Heuchera* is more sensitive to climate than that of other plants.

4.3.3 The Determination of Economic Irrigation Treatment in Mixed Species Planting Scheme in Different Cities and Phases

In terms of the mixed species planting scheme, a new method of irrigation treatment design has been proposed. The method from Data Standardization in statistics called Z-score (also a Standard Score) has been used to calculate and determine the economic irrigation treatment in mixed species planting scheme, taking into consideration the following two factors: 1) plant records have different units (e.g., plant height and spread use units of length, while the number of leaves is recorded with unit of quantity), and 2) the maximum natural growth size of each plant species is different (e.g., the size of *Vinca major* 'Variegata' naturally is greater than that of *Hosta* 'Blue Mouse Ears').

> "*….Data standardization is the process of converting data to a common format to enable users to process and analyse it. Different datasets may contain different variables, such as place, time, and subject. In order to analyse the data from disparate sources and units, it is necessary to convert data into a uniform format…. In statistics, the Standard Score is the number of standard deviations by which the value of a raw score is above or below the mean value of what is being observed or measured….*"
>
> *Gal and Rubinfeld (2019)*

The equation has been original proposed by author in order to calculate and determine the economic irrigation treatment for plants in LWS (Equation 6.1). Through method of Z-score from Data Standardization, the changes of plant height (*Z-score of changes in plant height, called ZH*), plant spread (*ZW*) and plant leaf number (*ZL*) can be calculated at the same time as they use the same units. The degree of effects on plant growth by irrigation treatment can be easily observed by the sum of transformed plant parameters. The economic irrigation treatment is the treatment that has smallest value in different *Qi* treatments (*Q1*, *Q2* and *Q3* means the Dry, the Medium and the Wet treatment) in the given time (phase).

$$Qi = \frac{ZHi + ZWi + ZLi}{QAi \times Qai}$$

Where *Qi* is the total value of Z-score of plant growth under the *i* irrigation treatment,
ZHi is the total value of Z-score of changes in plant height under the *i* irrigation treatment,
ZWi is the total value of Z-score of changes in plant spread under the *i* irrigation treatment,
ZLi is the total value of Z-score of changes in plant leaf number under the *i* irrigation treatment,

QAi is the total value of Z-score of aesthetic value under the *i* irrigation treatment,
Qai is the total value of Z-score of changes in aesthetic value under the *i* irrigation treatment.

Since the actual maximum and minimum values of plant growth are uncertain, the total value of Z-score is acquired through the following equation:

$$Z = \frac{x - \mu}{S}$$

Where *x* is the import data of plant growth, *μ* is the mean of the plant growth, *S* is the sample standard deviation of the plant growth.

Therefore, the equations of the total value of Z-score for changes in plant height (*ZH*), plant spread (*ZW*) and plant leave numbers (*ZL*) are as follows:

$$ZHi = \sum_{m=1}^{n} \frac{mhi - \mu mH}{SmH} = \frac{1hi - \mu 1H}{S1H} + \frac{2hi - \mu 2H}{S2H} + \cdots + \frac{mhi - \mu mH}{SmH}$$

Where the *ZHi* is the total value of Z-score of plant height under the *i* irrigation treatment, when the set of changes of plant height are: First plant species 1H = {1h1,1h2,1h3...}, Second plant species 2H = {2h1,2h2,2h3...}, M plant species mH = {mh1,mh2,mh3...}

$$ZWi = \sum_{m=1}^{n} \frac{mwi - \mu mW}{SmW} = \frac{1wi - \mu 1W}{S1W} + \frac{2wi - \mu 2W}{S2W} + \cdots + \frac{mwi - \mu mW}{SmW}$$

Where the *ZWi* is the total value of Z-score of plant spread under the *i* irrigation treatment, when the set of changes of plant spread are: First plant species 1W = {1w1,1w2,1w3...}, Second plant species 2W = {2w1,2w2,2w3...}, M plant species mW = {mw1,mw2,mw3...}

$$ZLi = \sum_{m=1}^{n} \frac{mli - \mu mL}{SmL} = \frac{1li - \mu 1L}{S1L} + \frac{2li - \mu 2L}{S2L} \ldots + \frac{mli - \mu mL}{SmL}$$

Where the *ZLi* is the total value of Z-score of plant leaf number under the *i* irrigation treatment, when the set of changes of plant leaf number are: First plant species 1L = {*1l*1,*1l2*,*1l3*...}, Second plant species 2L = {2l1,2l2,2l3...}, M plant species mL = {ml1,ml2,ml3...}

In order to meet the aesthetic pleasure, the changes of aesthetic rating need to be positive and the raw values of aesthetic rating should be greater than 4. The value of aesthetic rating for each plant species will be transformed by the following rules:

- The value of changes in plant aesthetic rating marks 1 when the changes of plant aesthetic rating are positive and of zero value (plant aesthetic rating is increasing or remains unchanged).
- The value of changes in plant aesthetic rating marks 0 when the changes of plant aesthetic rating are of negative value (plant aesthetic rating is decreasing).

- The value of plant aesthetic rating marks 1 when the plant aesthetic rating is greater than or equal to 4 (plant aesthetic rating is within an acceptable range).
- The value of plant aesthetic rating marks 0 when the plant aesthetic rating is lower than 4 (plant aesthetic rating is not acceptable).

The equations of the changes in aesthetic rating (*Qa*) and plant aesthetic rating (*QA*):

$$Qai = \prod_{m=1}^{n} mai = 1ai \times 2ai \times \ldots \times mai$$

Where the *Qai* is the total value of changes in plant aesthetic rating under the *i* irrigation treatment, when the set of changes of plant aesthetic rating are: First plant species 1a = {1a1,1a2,1a3...}, Second plant species 2a = {2a1,2a2,2a3...}, M plant species ma= {ma1,ma2,ma3...}

$$QAi = \prod_{m=1}^{n} mAi = 1Ai \times 2Ai \times \ldots \times mAi$$

Where the *QAi* is the total value of plant aesthetic rating under the *i* irrigation treatment, when the set of changes of plant aesthetic rating are: First plant species 1A = {1A1,1A2,1A3...}, Second plant species 2A = {2A1,2A2,2A3...}, M plant species mA = {mA1,mA2,mA3...}

The value of Q1 (the dry treatment), Q2 (the medium treatment) and Q3 (the third treatment) can be calculated by import relative data. The economical irrigation treatment is the treatment that caused the smallest value among Q1, Q2 and Q3.

However, when Q1, Q2, and Q3 are all N/A (when translated value of aesthetic rating is 0, all the irrigation strategies cannot meet the aesthetic pleasure requirements), the economical treatment is the treatment that resulted in minimal plant growth, taking no account of the aesthetic rating (because all transformed data of aesthetic rating are set to 1).

The results of economical treatment about Exp 2 are presented in Table 4.13. There are two examples of calculation in the Appendix.

Table 4.13 The economical irrigation treatment for different plant species in different cities and phases at mixed species planting scheme

PLANT SPECIES	2019 EXP 2 (THE MIXED SPECIES PLANTING SCHEME)			
	SHEFFIELD, UK		JINGMEN, CN	
	Phase 1	Phase 2	Phase 1	Phase 2
Vinca major 'Variegata'	Dry	Wet	Dry	Dry
Hosta 'Blue Mouse Ears'	Wet	Medium	Medium	Medium
Heuchera 'Marmalade'	Medium	Wet	Medium	Wet
Mixed	Medium	Wet	Medium	Wet

4.3.4 Discussion of Hypotheses

4.3.4.1 Some species would outcompete others in the mixed species planting scheme in the same LWS unit with limited natural resources (e.g., nutrition, water, sunshine)

In the mixed species planting scheme in Experiment 2, plant competition is another important factor affecting plant growth in addition to climate changes and irrigation treatments. This is because that when plants grow in two or more species in confined space (containers), they compete for limited natural resources (Weaver and Clements, 1938). Plant death is an obvious sign of plant competition. However, there is no plant dead recorded from the observation in Exp 2, and this may be due to 1) limited experiment time (only 2 months), and 2) the irrigation system keeps the soil in a constant range of moisture level. On the other hand, the detail of negative plant growth in Table 4.14 is another evidence to explore the plant competition in a certain extent.

Table 4.14 The number of negative increasing in plant growth in different species, plant physical index, and cities in Exp 2 (the data includes two phases (Phase 1 is May to June, Phase 2 is July to August) of Experiment 2 at 2019)

INDEX	IRRIGATION TREATMENT	Vinca CN	Vinca UK	Hosta CN	Hosta UK	Heuchera CN	Heuchera UK
PLANT HEIGHT	Dry	3/40	1/40	7/40	16/40	10/40	2/40
	Medium	0/40	0/40	7/40	16/40	17/40	5/40
	Wet	2/40	0/40	14/40	11/40	8/40	7/40
Total		5/120	1/120	28/120	43/120	35/120	14/120
PLANT SPREAD	Dry	5/40	2/40	11/40	7/40	18/40	2/40
	Medium	7/40	0/40	13/40	9/40	21/40	5/40
	Wet	3/40	0/40	14/40	3/40	12/40	1/40
Total		15/120	2/120	38/120	19/120	51/120	8/120
PLANT LEAF NUMBER	Dry	5/40	0/40	2/40	3/40	1/40	0/40
	Medium	0/40	0/40	1/40	6/40	5/40	0/40
	Wet	0/40	0/40	8/40	5/40	10/40	0/40
Total		5/120	0/120	11/120	14/120	16/120	0/120
TOTAL		25/360	3/360	77/360	76/360	102/360	22/360
PROPORTION		7%	1%	21%	21%	28%	6%

Vinca is the species that has the least dieback in those three plant species (Table 4.14). Only an average of 4% negative increase (e.g., plant wilt) is shown in all *Vinca* species in such mixed planting scheme. Most dieback in *Vinca* is observed in the plant spread in CN. *Hosta* is another species with two cities' dieback proportions close to each other (relatively high as nearly 21%). Evidence shows that most dieback of this species is shown in the plant spread in CN and the plant height in UK, and it occurs more in the medium and the wet treatments. *Heuchera* is the plant species that has significant difference of dieback occurrence between CN (28% in average) and UK (6% in average). The negative growth of plants mainly appears in the plant spread with an average of 42.5% (51/120) in the whole Exp 2. In conclusion, although there is no plant death recorded, the number of negative growths in Table 4.14 shows that *Vinca* may have relatively less growth pressure than other two species, especially in Jingmen. Further discussion about plant competition in both single planting and mixed planting scheme has been presented in Chapter 6.

Experiment 2 applied the SMS-based irrigation system which keeps soil moisture content in the environment dynamically stable, based on different irrigation treatments (e.g. dry treatment keeps the moisture between15% to 40%). Therefore, the water shortage is not one of main factors that led to plant death in this 2-month experiment. Generally, the plants compete for water mainly because of the constant loss of water in soil. The pressure on plants to absorb water from the soil increases as soil moisture reduces. When the pressure exceeds the tolerance of the plant, the plant will not be able to absorb water from the soil (Craine and Dybzinski, 2013). However, the soil moisture content of growing media will not fall to such a low level that the plants with relatively low drought tolerance cannot absorb water, because the irrigation system will help to maintain the moisture level within an acceptable range. The plant growth could slow down in the dry treatment. Different plants absorb water at different rates, which can further affect the growth of plants under different irrigation treatments. The plants that absorb soil water faster (e.g., plants with strong roots) can potentially make the water potential gradient of the plant's root greater and thus the soil dries faster compared with plants with slow water-absorption. In the dry treatment, plants with strong roots (e.g. *Vinca*) may broadly spread its roots and "steal" moisture from other plants (e.g. *Hosta*). However, this intrusion would have greater impact if without the irrigation system on LWS. In conclusion, the influence from plant competition for water could be reduced under the sensor-based irrigation system. But the competition could become fiercer over time as the plant with strong roots will further spread its roots.

In terms of the plant competition for light, the light limitation occurs when plant's demand for carbon exceeds canopy carbon supply (Craine and Dybzinski, 2013). For Experiment 2, plant competition is different in two different phases. In the first phase, the larger plants had an advantage in the competition for sunlight because they can receive more sunlight in LWS environment. It the second phase, high temperatures and strong sunlight intensity inhibited photosynthesis. Plants with smaller size that grow in the shadow under larger plants were more competitive. As for the plant competition for nutrition, the distribution of nutrition supply is proportional to the root density of different individuals (Reich et al., 2003; Craine et al., 2005). Plants with longer root length will absorb more nutrients from a given amount of soil (Craine and Dybzinski, 2013). For the LWS that only supported by irrigation system, the nutrition is the most important natural resource for plant compete. Plant species with strong and deep root (e.g., *Vinca*) are more competitive (Robinson, 2001).

In conclusion, the growth difference of plants in mixed species planting scheme of LWS is caused by not only the climate changes in different cities, but also the distribution of nutrition especially for such LWS with only support of irrigation system. Plants with strong and deep root have the growth advantage in such mixed planting LWS. The competition for sunlight will change over time, but plants with higher light tolerance will enjoy a growth advantage.

4.3.4.2 The effect on the plants under the mixed group in different irrigation conditions will vary with local climate factors (Sheffield, the United Kingdom comparing Jingmen, China).

Experiment results support this hypothesis. The plant growth analysis (Figs 4.36 to 4.39), the correlation analysis (Table 4.9 to 4.12) and the regression analysis (Table 4.15) provide plenty of evidence for the verification of this hypothesis. The effects of different irrigation treatments on plant growth will be affected by factors including: 1) climate changes, 2) plant characteristics (e.g., drought tolerance, plant root) and 3) plant dimensions (plant size, leaf density and number). Research findings are as below:

1) Under different irrigation treatments, the plant whose growth is most susceptible to local climate changes is *Heuchera*, followed by *Vinca,* and *Hosta* was least affected.

Environmental factors have different effects on the growth of different plants. According to the multiple linear regression analysis (Table 4.15), the values of Adjusted R Square in the growth of *Heuchera* are higher than those of other plant species, which shows that the growth of *Heuchera* has higher correlation with environmental factors than other species. *Heuchera*, in other words, is more sensitive to the climate changes. The effect of climate changes on the growth of *Vinca* and *Hosta* is limited as the correlations between the growth of plants and the changes of climate factors are relatively weak according to the SPSS analysis. As for the comparison between these two plant species, the correlation between plant growth and climate factors is slightly higher for *Vinca* than for *Hosta* as the values of Adjusted R Square of *Vinca* are slightly higher than *Hosta*'s, especially in terms of the plant height and the number of leaves.

2) Among the four monitored climate factors, temperature has the largest influence negatively, followed by relative humidly and pressure positively and the influence of precipitation is the weakest. The impacts of climate factors on the growth of three plant species are greater in the Sheffield than in Jingmen.

Firstly, the highest average value of the correlation between the climate factors and plant growth is of the temperature. This shows that the overall growth of three plant species will slow down with the increase of temperature. The correlation between temperature and plant growth is r = -0.499 for the *Vinca*, r = -0.583 for the *Hosta*, and r = -0.740 for the *Heuchera,* respectively. It shows that the rise of temperature poses greater growth inhibition on *Heuchera* than other plant species. This result may be related to plant's size and leaf density. For one thing, the high temperature promotes the transpiration of plants, while water loss leads to partial closure of stomata especially in the noon. For another, the strong sunlight results in the photoinhibition. In the case of mixed species planting scheme, *Hosta* is sheltered in the shadow of *Vinca* and *Heuchera* due to its relatively small size. Compared with *Heuchera, Vinca* has smaller leaf size and larger spacing between leaves. These factors combined lead to *Heuchera*'s greater sensitivity to temperature changes than other plant species. Secondly, the average values of relative humidity and pressure show a positive correlation (r = 0.577 and 0.535 respectively). The increase of those climate factors will benefit the plant growth. Among them, the total correlations of the humidity and growth and the pressure and growth under three different irrigation treatments are r = 0.585 and 0.485 for *Vinca*, r =0.448 and 0.439 for *Hosta* and r = 0.697 and 0.682 for *Heuchera*. Thirdly, the effect of precipitation on plant growth is the weakest as it has the smallest correlation value with plant growth. This may be attributed to the special structure of LWS. For example, the small surface of the growing media leads to limitation on rainwater collection. Overall, according to the climate changes, the temperature of Jingmen was about 10 degrees higher than that of Sheffield, and the air pressure and relative humidity were both higher in Jingmen in the same phase (Figs 4.32 to 4.35). Therefore, the performance of plant growth in Sheffield was greater than in Jingmen in the same phase.

3) Environmental factors have different effects on plant growth under different irrigation treatments. The plant affected most by the environment changes is the *Heuchera* under the dry treatment, while the plant least affected is the *Hosta* in the medium treatment.

(1) Among the three plant species, *Heuchera* has the largest value of Adjusted R Square under the dry treatments, especially for the plant height and spread (Table 4.15). This implies that *Heuchera* is more sensitive to climate changes under the dry treatment. This may be because that its root system of plant is weaker than *Vinca*'s, which leads to *Heuchera*s competitiveness in nutrition being weaker than *Vinca's*. In addition, because *Heucheras* has denser and larger leaves compared with other plants, it will be more affected by the environment in the open space on LWS. (2) For *Hosta*, the reason for the low sensitivity to the environment with the climate factors is that the shady plant characteristics is limited in such an open LWS environment, instead of the resistance of plant itself. An important evidence is that *Hosta* has greater growth in a relatively pressureless environment such as Sheffield in phase 1, compared with phase 2 when there even occurred dieback.

4) The effects of environmental factors on the growth of plant characteristics are different under different irrigation treatments. The most affected characteristic by the environment is the changes in plant spread of *Heuchera*, while the least affected characteristic is the changes in plant height of *Hosta*.

(1) the value of Adjusted R Square of changes in *Heuchera's* spread caused by climate factors is 0.622 (Table 4.15), which is the greatest value compared with the others, meaning that the plant spread of *Heuchera* is more susceptible to environmental changes. The main reason is that the width of *Heuchera* is more severely inhibited by the environment, including climate and plant competition, than other plant species in the phase 2 in Jingmen (Fig 4.37). (2) *Hosta's* plant height is least affected by environmental changes as the value of Adjusted R Square is only 0.130. This may be caused by the relative short plant height of *Hosta*, so the necessary sunlight is obtained by increasing the width of the plant.

Table 4.15 the value of Adjusted R Square in multiple linear regression analysis about plant growth and climate factors (air temperature, relative humidity, precipitation, air pressure)

(Dependent variable is changes in plant height, plant spread and leaf number, the predictors is air temperature, relative humidity, precipitation and air pressure) (Exp2. in 2019)

PLANT SPECIES	TREATMENTS	CHANGES IN PLANT HEIGHT	CHANGES IN PLANT SPREAD	CHANGES IN LEAF NUMBER
Vinca major 'Variegata'	Dry	0.118	0.253	0.464
	Medium	0.214	0.180	0.463
	Wet	0.106	0.07	0.406
	Total	0.253	0.282	0.534
Hosta 'Blue Mouse Ears'	Dry	0.293	-0.152	0.250
	Medium	0.260	-0.096	0.193
	Wet	0.516	0.152	0.260
	Total	0.130	0.444	0.383
Heuchera 'Marmalade'	Dry	0.679	0.614	0.588
	Medium	0.422	0.591	0.360
	Wet	0.661	0.445	0.683
	Total	0.601	0.622	0.606

4.4 CONCLUSION

Generally, the design of irrigation treatment under the mixed species planting scheme of LWS needs to consider the species and the characteristics (plant height, plant spread, leaf size and numbers) of plants. The growth of each individual plant could be affected by factors including irrigation treatments, climate factors, and plant competition under such mixed species environment on LWS.

The resources supplied manually from the support system in LWS will not be the main factor that affects the growth of plants. For instance, the nutrition and the sunlight could be the main resources plants compete for under the LWS with supported irrigation system. The plant with larger and stronger roots and with patches will have certain competitive advantages in the growing environment in LWS of mixed species planting scheme.

The effect on the plants in the mixed group in different irrigation conditions will vary with local climate factors (Sheffield, the United Kingdom vs Jingmen, China). However, it should be noted that plant growth having weak correlation with environmental factors does not mean that this plant species has strong growth capacity. For instance, *Hosta* showed a weak correlation between growth and environment: its growth was affected not only by the climate changes, but also by plant competition. However, the Experiment 2 shows that plant species that can tolerate higher temperature are better suited to the mixed species planting scheme in LWS.

Key Points in Experiment 2

- Plant growth in mixed-species planting scheme is affected by not only irrigation level, but also climate difference (e.g., cities).

- Plants with high drought tolerant species (*Vinca*) tend to experience less dieback than those considered less drought-tolerant (*Hosta* and *Heuchera*) in the mixed-species planting scheme.

- There are some suggestions of an irrigation support system to mitigate plant competition in LWS.

CHAPTER 5: EXP 3. THE EFFECT OF SINGLE PLANT SPECIES CHOICE, IRRIGATION AND DEGREE OF SHADING OF GROWTH

Plants in the previous two experiments were affected by climatic factors. Living wall systems can be placed in various climates, but also in various aspects in relation to a building's position. They can be predominately south, west, north or east facing, and thus experience different amounts of direct sunlight. The construction of the modules too can affect the degree of shading a given plant experiences, for examples those on a lower tear may be shaded by those above. The aspect a LWS faces can determine the plant species selected (Livewall, 2021; Scotscape, 2021; Treebox, 2021).

The objective of this experiment was to determine how shading and irrigation supply affected plant development when only a single taxon was in the growing module (i.e., no competition between species for the water or light available). Plant recommendations in practice may vary based on many factors, but the principle explored in this experiment was to simply compare consistent full sun v consistent full shade throughout the day, as extremes of the sort of light regimes may face on a commercial wall. Water supply may mitigate a plants response to light – for example heavy irrigation allowing for growth in full sun, and this aspect was introduced to determine how plants responded in both light environments, with excess and limited water supplies. Thus the author developed a simplified factorial experiment and only focused on the two extreme shading conditions (not covered ('sun') and fully covered ('shadow')) for two irrigation treatments (the dry treatment (15% to 40% soil moisture content) and the wet treatment (65% to 90% soil moisture content)).

The following hypotheses were to be tested:

- Plants grown in not covered (sun) environment will grow more strongly than those in fully covered (shadow) environment.
- Plants under the dry treatment will not grow as well as those in the wet treatment, and this will be more noticeable in the full sun environment.
- Large leaved plants that reputably can acclimatize to shade (e.g., *Heuchera*) will perform better in the shadow environment.

5.1 MATERIAL AND METHODS

In order to achieve the experimental aim and verify the experimental hypotheses above, a new experiment -Experiment 3 was set in an open space near the Experiment 1 and 2 in Sheffield, UK (Fig 5.1). This experiment used two plant species (*Hosta* and *Heuchera* (see Chapter 2.5)) and continued from 1 Sep 2019 to 30 Oct 2019, and was not replicated in CN.

5.1.1 Experimental Design

Experiment 3 was divided into two groups based on the different shading treatment. The group applied Sun Treatment (not covered, fully opened in the environment) is called 'Sun', while the group used Shadow Treatment (covered by three layers of "Blooma Polyvinyl chloride (PVC) Mosquito Netting" (B&Q, Eastleigh, Hampshire, United Kingdom)) is called 'Shadow'. All those two groups were placed on the temporary wooden bed (1200mm length x 1200mm width x 150mm height) to simulate the same LWS environment at the first level on the previous LWS system. This wooden bed is made by 20 mm thick wooden planks with approximately 50 mm gaps in order to meet the drainage requirement. As the experimental site has a certain slope, a gradienter was used to rectify the angle of the wooden bed, bricks were inserted into one side of the wooden bed to keep it level.

Figure 5.1 The arrangement of different experimental groups in Experiment 3

Two plant species were selected namely *Vinca major* 'Variegata' and *Heuchera* 'Marmalade' (see Chapter 2.5). Each group (e.g., Sun, Shadow) used 48 plants (24 plants for each plant species). 6 plants of the same species were combined as a sub-group unit (2 pots per row x 3 pots per column) and used the same irrigation treatment (see Table 5.1 and Fig 5.2). 2-Litre plant pots (B&Q, Eastleigh, Hampshire, United Kingdom) was used as the standard plant units for Experiment 3 as this pot can accommodate a similar volume of growing media as the container in LWS, and can avoid the species competition for water, light and nutrients. To partially minimize the effect of plant ageing (and residual effects on plant growth from the earlier growing scheme), plants were pruned to a similar size in each place (15 x 15 cm, h x b) (see Chapter 2.5). The growing media for this experiment is also "CANNA Coco Professional Plus" from CANNA company (CANNA BV, London, UK), the same as Experiment 1 and 2.

Table 5.1 The plant locations and irrigation treatments in Experiment 3

TIME	LOCATION	PLANT LOCATION AND IRRIGATION TREATMENT							
		Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
1st September 2019 To 31st October 2019	Row 6	Vinca 1	Vinca 2	Heuchera 1	Heuchera 2	Vinca 1	Vinca 2	Heuchera 1	Heuchera 2
	Row 5	Vinca 3	Vinca 4	Heuchera 3	Heuchera 4	Vinca 3	Vinca 4	Heuchera 3	Heuchera 4
	Row 4	Vinca 5	Vinca 6	Heuchera 5	Heuchera 6	Vinca 5	Vinca 6	Heuchera 5	Heuchera 6
	Row 3	Heuchera 1	Heuchera 2	Vinca 1	Vinca 2	Heuchera 1	Heuchera 2	Vinca 1	Vinca 2
	Row 2	Heuchera 3	Heuchera 4	Vinca 3	Vinca 4	Heuchera 3	Heuchera 4	Vinca 3	Vinca 4
	Row 1	Heuchera 5	Heuchera 6	Vinca 5	Vinca 6	Heuchera 5	Heuchera 6	Vinca 5	Vinca 6

*Red colour for dry treatment, green colour for wet treatment

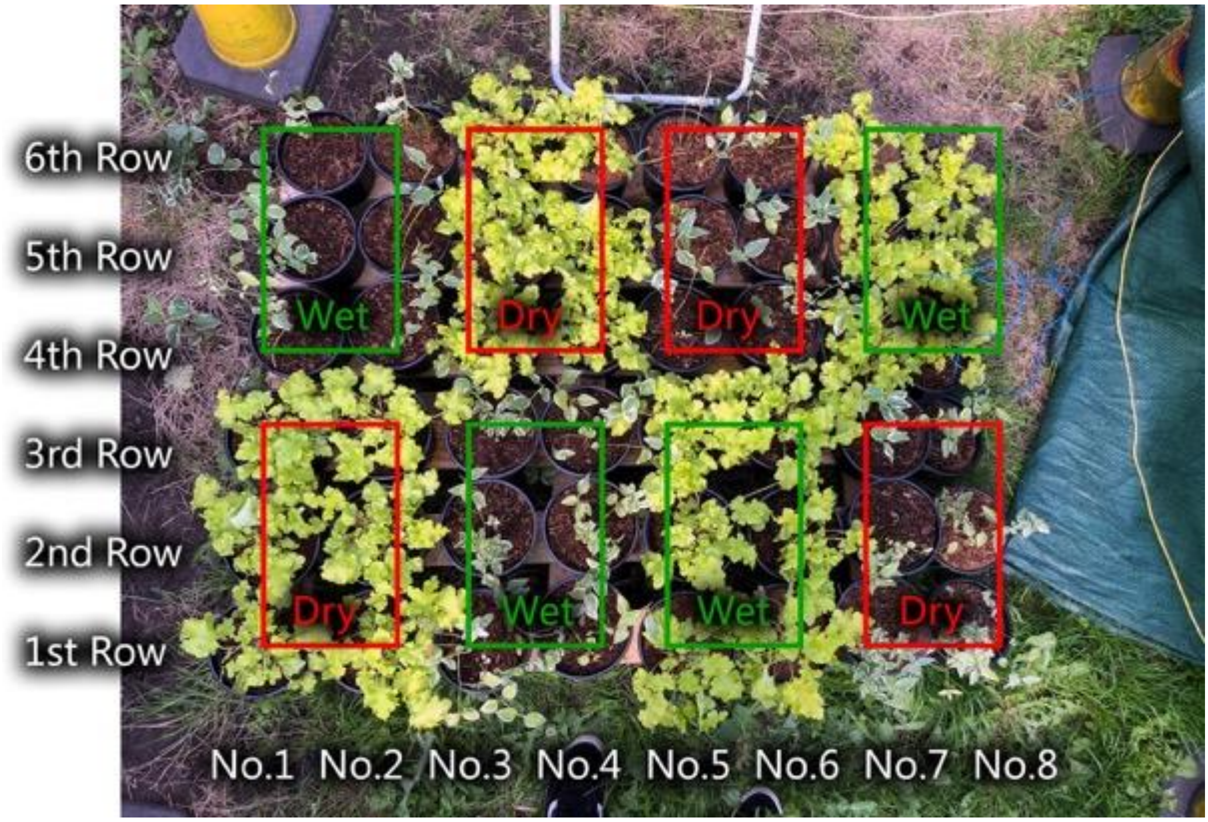

Figure 5.2 The plant locations and irrigation treatments in Experiment 3

During the process of transplant, the bottom of the standard 2L plant pot was covered with a 40 mm layer of coir before the transplantation. After that, the plants were carefully removed from the original pots and the original soil were carefully removed to reduce possible effects from the nutrients and viruses in the original soil. In order to ensure the plant health and quality which could be potentially affected by pruning and transplantation from original pots into the standard plant container units, all plants were cultivated for another week before the recommencement of the experiment.

For safety reason (e.g., electricity), the irrigation treatment was conducted by author rather than controlled by computer-based irrigation system as in Exp 1 and 2. The soil moisture content of each pot unit was measured by ML3 ThetaKit Soil Moisture Portable Kits (moisture accuracy of ± 1%, Delta-T Devices Ltd, London, UK) and monitored manually at 14:00 pm every day. When the soil moisture content reached the threshold values of the dry treatment (15% to 40% soil moisture content) or the wet treatment (65% to 90% soil moisture content), the required amount of water was transported to the plants manually in order to keep the moisture content within the range set.

5.1.2 Data Collection and Statistical Approaches

The method of meteorological data collection was same as the Experiment 1 and 2, but only from MetOffice (Met Office, 2021). The value of Photosynthetically Active Radiation (PAR) is the mean value of records from 12:00 to 13:00 in a day by the author through the SunScan Probe type SS1 (0.3 $\mu mol.m^{-2}$. s^{-1}resolution with the accuracy of ± 10%, Delta-T Devices Ltd, London, UK). The data of growing media moisture content for each plant container pot was measured manually at 13:00 pm every day by ML3 ThetaKit Soil Moisture Portable Kits. The physiological data about plant growth focused same four different indicators as Exp 1 and 2 and carried out every 15 days (the dates were 1, 15, 30 September, 15, 31 October) during noon.

Statistical Approaches

The Two-Way ANOVA and LSD (Least Significant Difference) (IBM® SPSS® Statistics 25) was used to explore the significance between level of shading and irrigation on key growth / quality parameters. To discuss whether there is interactive effect among the two independent variables of shading and irrigation treatments for each two species separately. All data of the plant growth were analysed in the relative increase value rather than actual raw value, so as to avoid the misleading the experimental results. In order to run LSD property, Data Transformation ‘LG10 (max+1-x)’ is also used to ensure the normal distribution. Results of statistical difference levels generated from table of Multiple Comparisons in Post Hoc Tests and were presented on Figures and Tables as letters, with mean values showing significant difference being represented by different lowercase letters (e.g., a, b). Kruskal-Wallis H test is used to analyse the correlation between plant aesthetic performance, shading and irrigation treatment, because the dependent variable of plant’s aesthetic rating falls into the category of ordinal categorical variable. The Simple Linear Regression (IBM® SPSS® Statistics 25) was used to analyse the correlation between the Photosynthetically Active Radiation (PAR) and plant development under different irrigation treatments in different plant species. All the graphs shown below present the transformed data to make it easier for the reader to understand. An alpha level of 0.05 was used for all statistical analysis.

5.2 RESULTS

5.2.1 *Vinca major* 'Variegata'

1）The changes of plant height (extension growth)

No significant difference was found in the height change of *Vinca* under the dry and the wet treatment either in the sun group or the shadow group ($p < 0.05$, LSD) (Fig 5.3). However, the plants in the shadow group grew slightly taller (23-36 mm) than those in the sun group (3-9 mm) on the whole in terms of the mean value of plant height.

Plants under the dry treatment in the sun group and under the wet treatments in the shadow group grew slightly higher than those under other irrigations with the same degree of shading. However, there was no visually noticeable plant height difference in the sun group, while a slight difference was found in the shadow group.

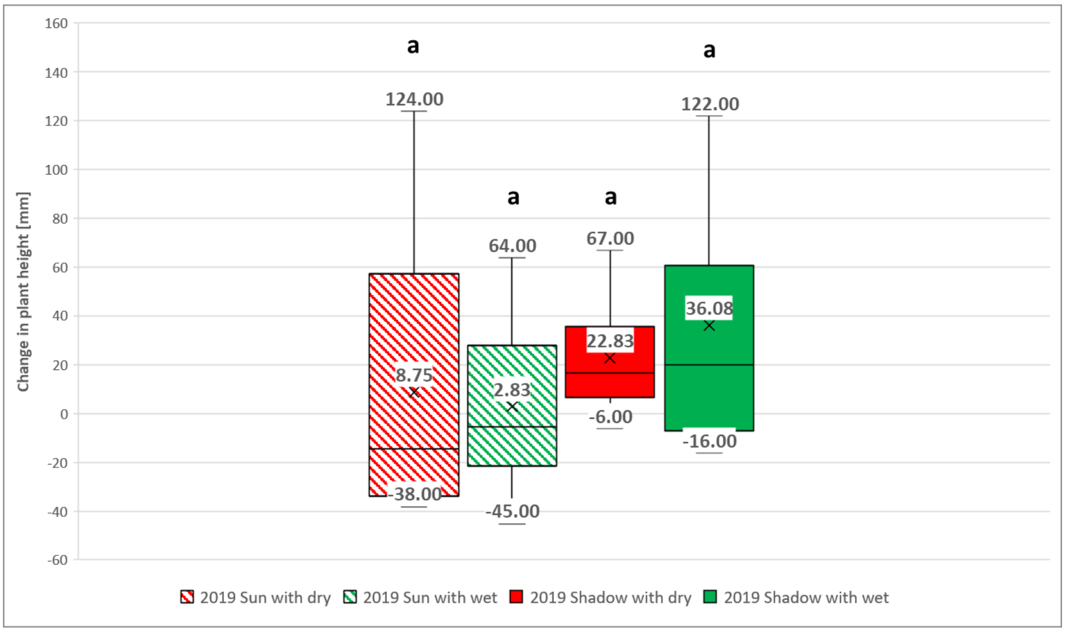

Figure 5.3 The mean change in the plant height of *Vinca major* 'Variegata' under different irrigation treatments and degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

2）The changes of plant spread

Overall, plants in the sun group had more lateral growth those in shadow ($p > 0.05$) (Fig 5.4). Specifically, lateral plant growth was significantly greater under the wet treatment (by about 70 mm) compared to the dry when plants were grown in full sun ($p < 0.05$). Conversely, growth was marginally greater (not significant) with the dry regime, compared to the wet treatment, when in the shadow (Fig 5.4).

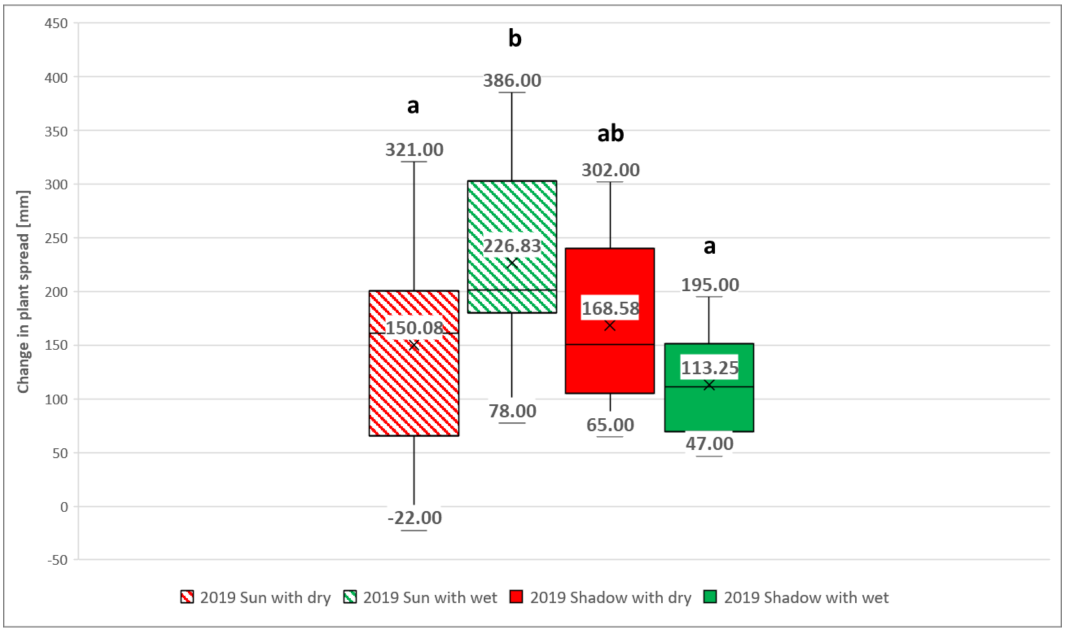

Figure 5.4 The mean change in the plant spread of *Vinca major* 'Variegata' under different irrigation treatments and degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

The amount of light strongly affected the number of new leaves, with plants in the sun treatment growing significantly greater numbers. Plants here typically generated between 217 and 238 new leaves (Fig 5.5). The dry, sun treatment resulted in the greatest number of new medium sized leaves (189.17 per plant, Table 5.2) and small leaves (20.17 per plant).

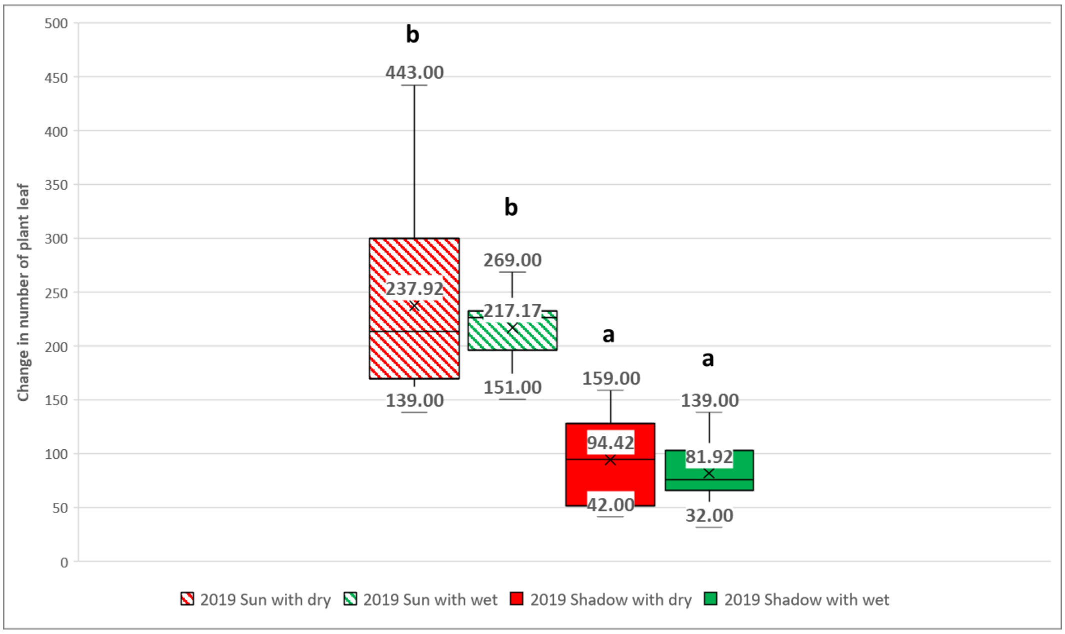

Figure 5.5 The mean change in the number of the plant leaves of *Vinca major* 'Variegata' under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

Table 5.2 The mean change in numbers of different size of plant leaves of *Vinca major* 'Variegata' under different shading and irrigation treatments in the Sheffield, United Kingdom (Exp3. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Sun group under dry treatment	237.92	24.63	28.58	2.10	189.17	25.11	20.17	25.11
Sun group under wet treatment	217.17	9.87	31.08	2.26	168.83	10.47	17.25	3.69
Shadow group under dry treatment	94.42	11.85	17.25	2.33	68.08	9.67	9.08	1.55
Shadow group under wet treatment	81.92	9.52	17.17	9.52	57.83	9.09	6.92	1.91

4）The changes of plant aesthetic ratings

The increase of plant quality was noted more in the sun group than in the shadow group (Fig 5.6). Plants in the drier irrigation within the shadow showed no improvement in quality (i.e., significantly less compared to both treatments in the sun, p > 0.05), but this was the best overall quality treatment anyway, both before and after the experiment (Fig 5.7).

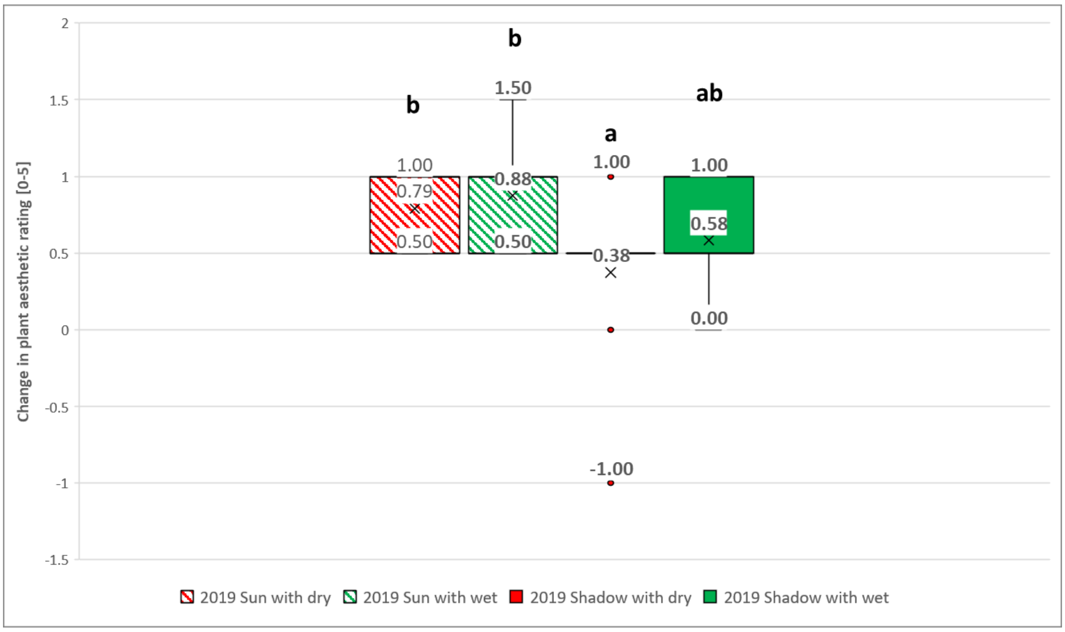

Figure 5.6 The mean change in the aesthetic ratings of *Vinca major* ‘Variegata’ under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

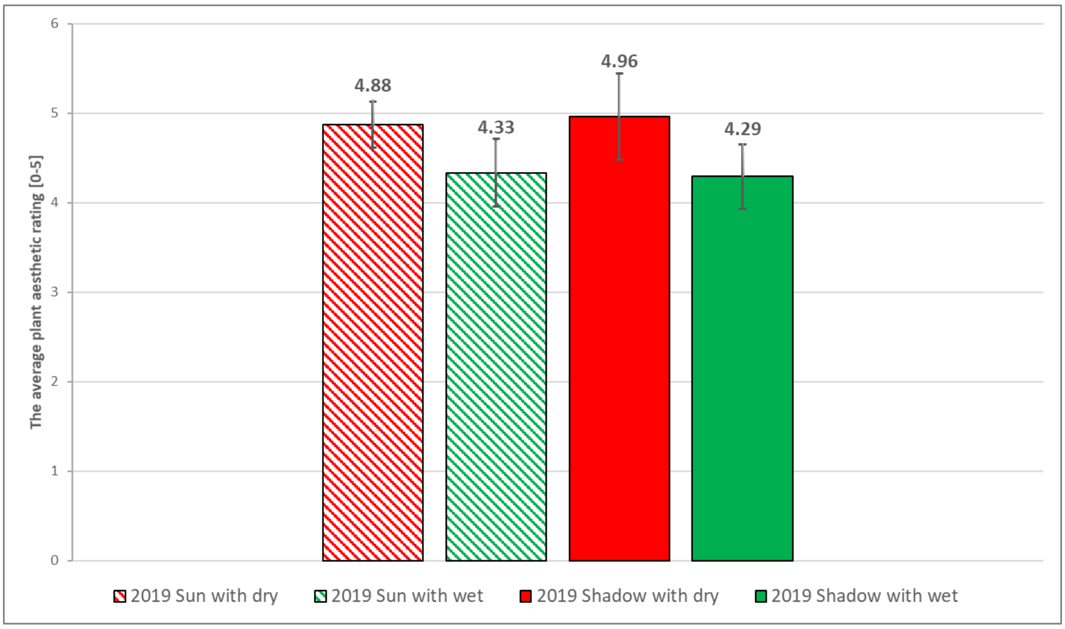

Figure 5.7 The mean value of aesthetic ratings of *Vinca major* 'Variegata' under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom (bars represent standard deviation)

5.2.2 *Heuchera* 'Marmalade'

1) The changes of plant height

Dieback appeared and contributed to the changes of *Heuchera*'s height in all treatments (Fig 5.8). Overall, plant heights reduced more in the sun group (43-39 mm) than in the shadow group (25-17mm).

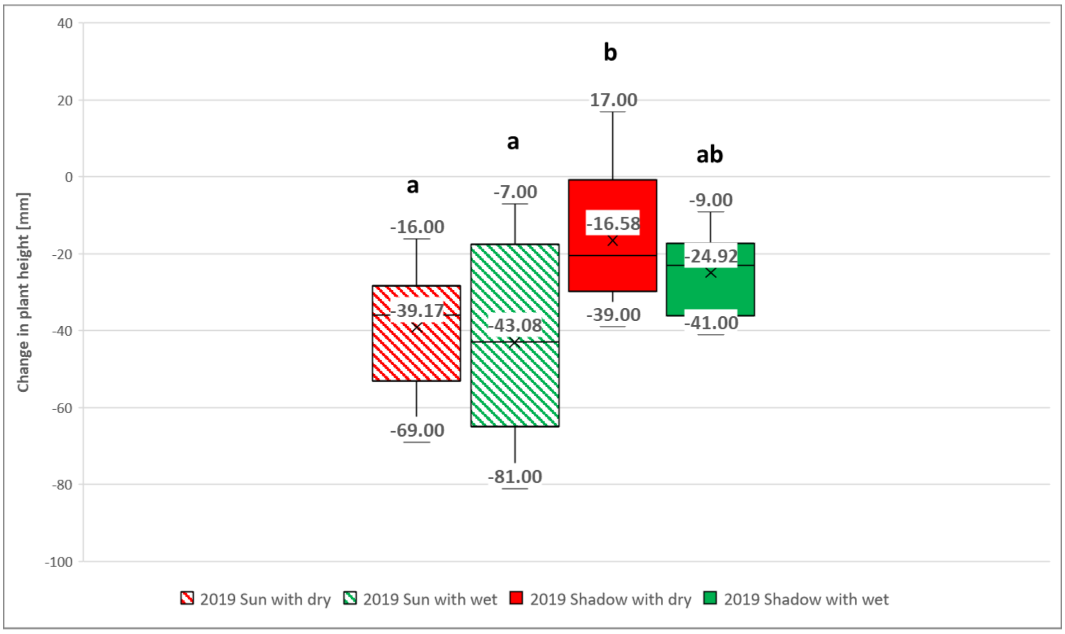

Figure 5.8 The mean change in the plant height of *Heuchera* 'Marmalade' under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

2) The changes of plant spread

The shade encourage some lateral growth in this taxa, with an extension in growth being noted in both the dry (33mm) and wet (42mm) treatments within the shadow (Fig 5.9). In contrast there was some dieback in the wet treatment in full sun.

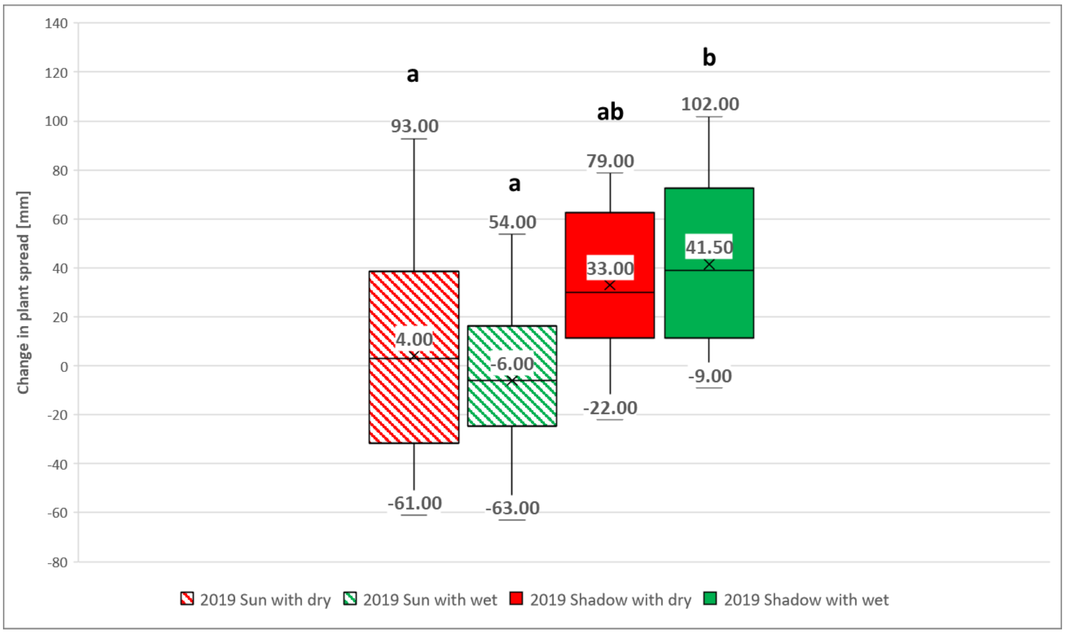

Figure 5.9 The mean change in the plant spread of *Heuchera* 'Marmalade' under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

3）The changes of numbers of plant leaves

Somewhat in contrast to the data on growth extension, new leaf generation was greatest in the full sun / wet irrigation treatment, with an overall increase in approximately 160 leaves per plant (Fig 5.10). There was a mean of 20 new small leaves in this treatment compared to only 7-10 in other treatments (Table 5.3). Even plants on the dry sun treatment generated significantly ($P < 0.05$) more leaves than those in the shadow treatments.

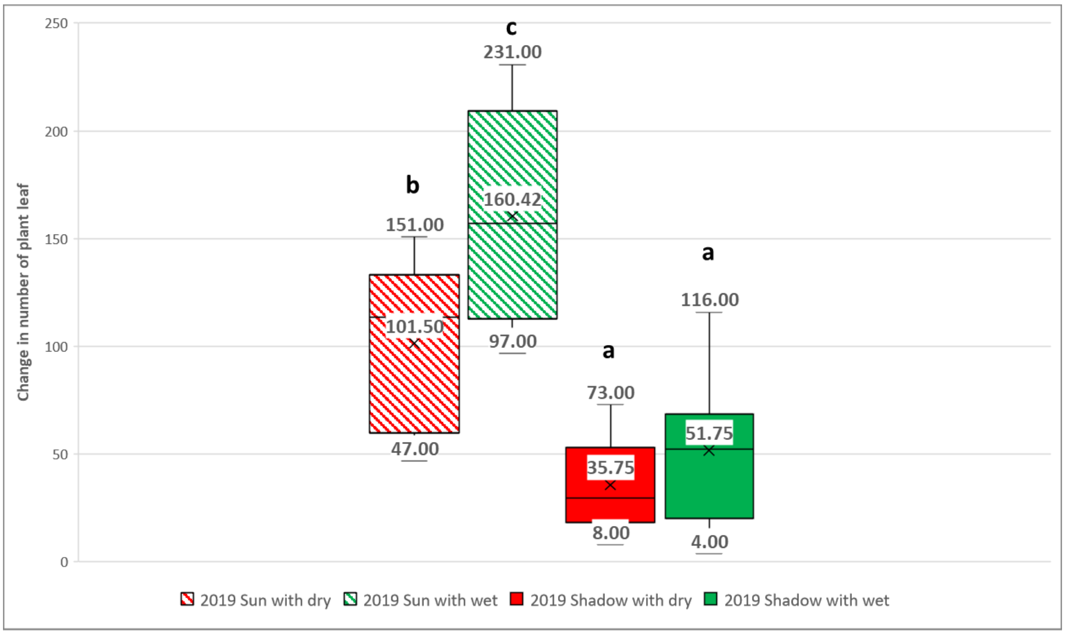

Figure 5.10 The mean change in the number of the plant leaves of *Heuchera* 'Marmalade' under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

Table 5.3 The mean change in numbers of different size of plant leaves of *Heuchera* 'Marmalade' under different shading and irrigation treatments in the Sheffield, United Kingdom (Exp3. in 2019)

TREATMENT	ALL SIZE		LARGE SIZE		MEDIUM SIZE		SMALL SIZE	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Sun group under dry treatment	101.50	11.04	57.58	7.50	34.25	6.61	9.67	1.41
Sun group under wet treatment	160.42	14.06	71.50	6.40	67.58	10.91	21.33	2.94
Shadow group under dry treatment	35.75	6.51	13.50	2.02	14.17	4.90	8.08	1.71
Shadow group under wet treatment	51.75	9.82	24.25	2.69	20.75	6.29	6.75	2.38

4） The changes of plant aesthetic ratings

Plants in the dry regime within full sun, were associated with a loss of aesthetic quality during the experimental period (Fig 5.11), and were associated with the lowest quality of all plants by the end of the experiment (Fig 5.12). In contrast plants grown dry within the shadows, were linked to best quality (Fig 5.12), even though they had lost some quality during the treatment phase (Fig 5.11).

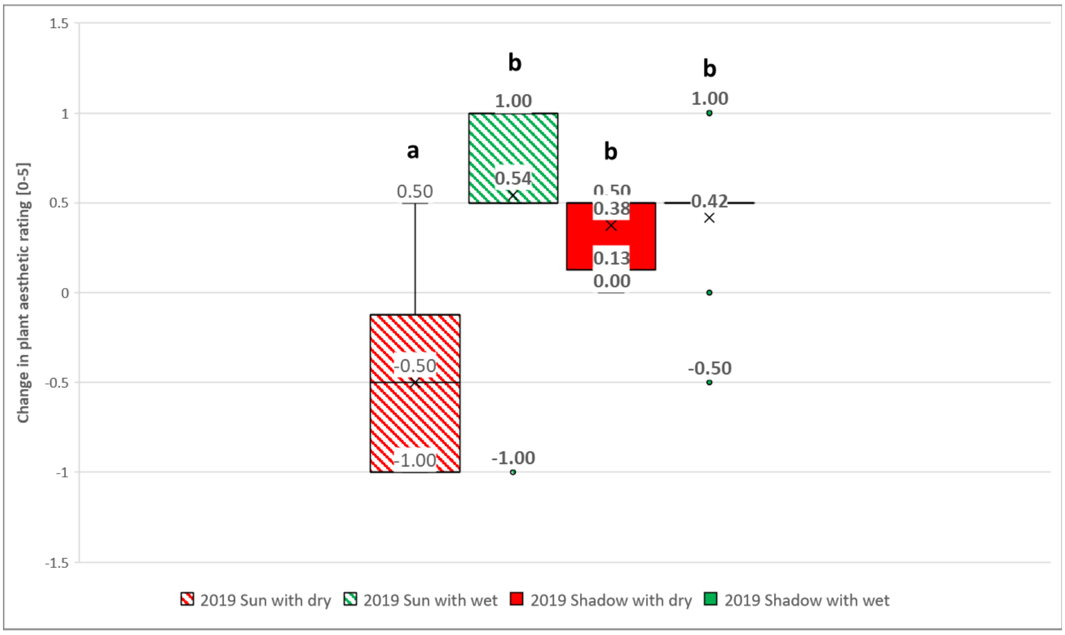

Figure 5.11 The mean change in the aesthetic ratings of *Heuchera* 'Marmalade' under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom, (three data of each bar are the highest value, the lowest value and the mean value) (NB. the letters on the graph denote difference from the transformed values)

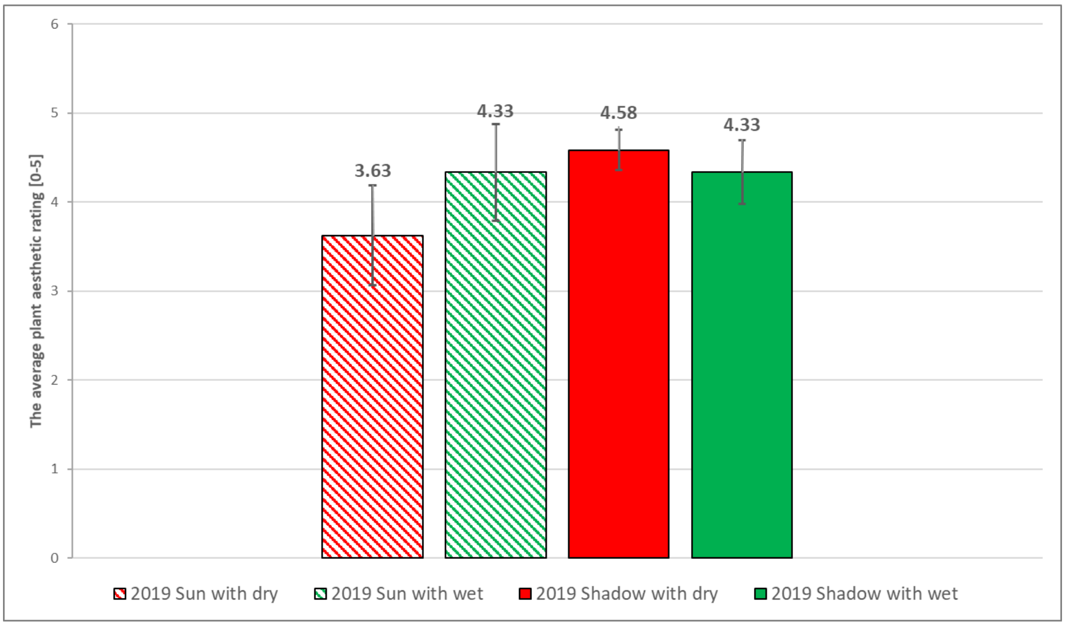

Figure 5.12 The mean value of aesthetic ratings of *Heuchera* 'Marmalade' under different irrigation treatments and different degrees of shading in Sheffield, the United Kingdom (bars represent standard deviation)

5.2.3 Interaction Effect Analysis

Table 5.4 The interaction analysis between shading and irrigation treatments on plant growth of two species by Two-way ANOVA

PLANT SPECIES	PLANT PARAMETERS	INTERACTION EFFECT	SIMPLE MAIN EFFECT			
		Shading and irrigation	Sun (dry VS wet)	Shadow (dry VS wet)	Dry (sun VS shadow)	Wet (sun VS shadow)
Vinca	Height	0.62	0.73	0.45	0.42	0.06
	Spread	0.01*	0.02*	0.09	0.56	0.00*
	Leaf	0.79	0.34	0.57	0.00*	0.00*
	Aesthetic	0.57	0.59	0.18	0.01*	0.07
Heuchera	Height	0.67	0.59	0.26	0.00*	0.02*
	Spread	0.39	0.51	0.58	0.06	0.00*
	Leaf	0.05*	0.00*	0.30	0.00*	0.00*
	Aesthetic	0.00*	0.00*	0.82	0.00*	0.50

*. Correlation is significant at the 0.05 level (2-tailed).

Implementing a two-way ANOVA on the data showed significant interactions for plant spread ($F(1, 44) = 8.629$, $p = 0.01$, $\eta^2 = 0.164$) in *Vinca* and plant leaf number ($F(1, 44) = 4.018$, $p = 0.05$, $\eta^2 = 0.084$) and aesthetic rating ($F(1, 44) = 15.158$, $p = 0.00$, $\eta^2 = 0.256$) in *Heuchera* (Table 5.4). In *Vinca*, the wet irrigation in the sun treatment was seen as advantageous, where in contrast wet treatment in the shade were less effective than the dry, i.e. the degree of light was affecting the effectiveness of the wet treatment. Similarly, in *Heuchera* in terms of overall aesthetic ratings the wet treatment was the more advantageous in full sun, but a slight disadvantage in the shadow.

5.2.4 Correlations Between Photosynthetically Active Radiation (PAR) and Plant Growth

Generally, the strength of Photosynthetically Active Radiation (PAR) gradually decreases with time in the Sun group (Fig 5.13). The value of PAR started from on average 442.1 (μmol. m^{-2}. s^{-1}) in the first 15 days and reduced to on average 297.5 (μmol. m^{-2}. s^{-1}) in the last 15 days. While the changes of PAR value were more stable in the Group of Shadow, which is on average 17.8 (μmol. m^{-2}. s^{-1}). The highest value of PAR of the sun group was on 03rd Sep 2019, being 1168.7 (μmol. m^{-2}. s^{-1}) on average while the lowest value is 135.3 (μmol. m^{-2}. s^{-1}) on 18th Sep 2019. The high point of PAR value of shadow group was reached on 03rd Sep 2019, being 62.8 (μmol. m^{-2}. s^{-1}) on average but dropped to the lowest of 2.8 (μmol. m^{-2}. s^{-1}) on average at 11st Oct 2019.

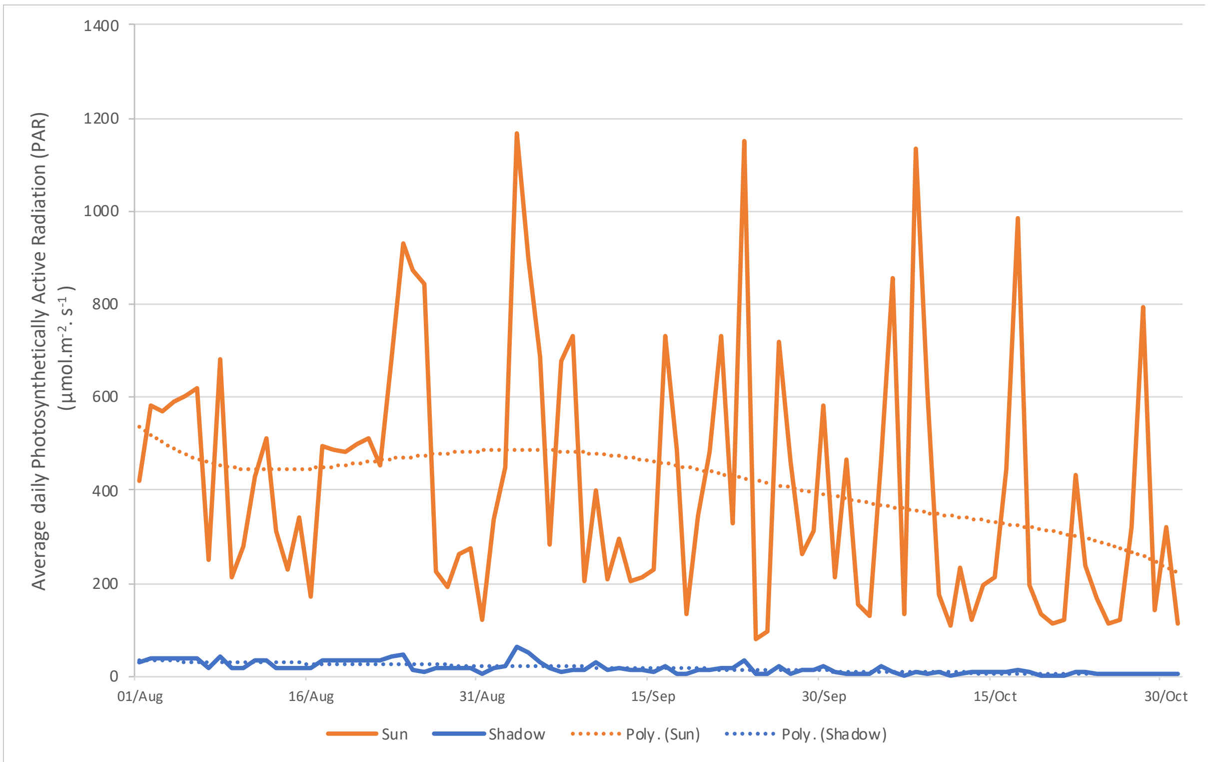

Figure 5.13 Average Photosynthetically Active Radiation (PAR) at sun group (Orange) and shadow group (Blue) from August to October 2019 in Sheffield, the United Kingdom

5.2.4.1 *Vinca major* 'Variegata'

Correlating plant parameters to PAR shows that *Vinca's* growth is mainly negatively related to PAR (Table 5.5). The strong correlation (|r|= 0.6 to 0.79) showed in the most plant parameters with PAR under all treatments and plant growth in shadow has stronger negative correlation than that in sun. Among that, the strongest correlation between plant growth and PAR is the plant spread (r = -0.937) and plant leaves (r = -0.958) when plant under shadow group and dry treatment.

Table 5.5 The Pearson correlation analysis between the Photosynthetically Active Radiation (PAR) and *Vinca major* 'Variegata' growth (Exp3. in 2019)

SHADING TREATMENT	IRRIGATION TREATMENT	PLANT HEIGHT	PLANT SPREAD	PLANT LEAVES
Sun group	Dry treatment	-0.721	-0.682	-0.656
	Wet treatment	-0.638	-0.483	-0.632
Shadow group	Dry treatment	-0.341	-0.937	-0.958
	Wet treatment	-0.761	-0.875	-0.892

**. The correlation is significant at the significance level of 0.01(2-tailed).
*. The correlation is significant at the significance level of 0.05 (2-tailed).

5.2.4.2 *Heuchera* 'Marmalade'

Both positive and negative correlations appeared in the correlation analysis between plant parameters and PAR with the same probability (Table 5.6). The positive correlation of PAR mainly related to the plant height, while negative correlation mainly related to the plant leaves. All correlations show strong correlations (|r|= 0.6 to 0.79), and some have very strong correlations (|r|= 0.8 to 1). Among them, the strongest positive correlation between plant parameters to PAR is the plant height (r = 0.977) under the shadow group with dry treatment, while strongest negative correlation is the plant leaves (r = -0.958) under the same treatments. In addition, the changes of PAR had a relatively stronger effect on plants in the shadow group than those in the sun group.

Table 5.6 The Pearson correlation analysis between the Photosynthetically Active Radiation (PAR) and *Heuchera* 'Marmalade' growth (Exp3. in 2019)

SHADING TREATMENT	IRRIGATION TREATMENT	PLANT HEIGHT	PLANT SPREAD	PLANT LEAVES
Sun group	Dry treatment	0.769	0.875	-0.694
	Wet treatment	0.816	0.752	-0.718
Shadow group	Dry treatment	0.977	-0.685	-0.958
	Wet treatment	0.939	-0.777	-0.863

**. The correlation is significant at the significance level of 0.01 (2-tailed).
*. The correlation is significant at the significance level of 0.05 (2-tailed).

5.2.5 Plant Overview Growth in Exp 3

Comparing the two species together, it is evident that *Vinca* generally performs well, with shoot extension still occurring in the shadow (Fig. 5.14) and plant spread in both sun and shadow (Fig 5.15). In contrast, *Heuchera* demonstrates shoot dieback at this time of year in both shadow and sun (Fig 5.14), with little lateral growth in either (Fig 5.15). Both plants develop new leaves however (Fig 5.16), and quality overall is not deficient, except with *Heuchera* in dry, sun (Fig 5.17).

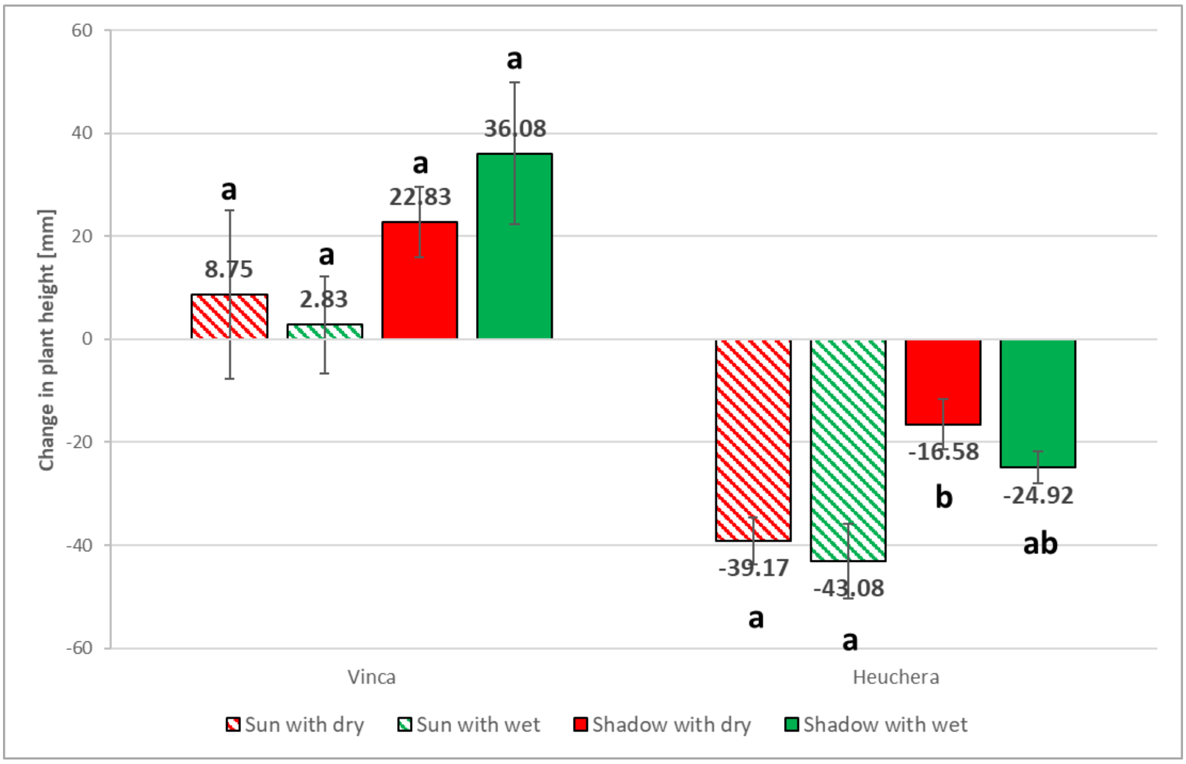

Figure 5.14 The mean change in plant height in Day 90 (two plant species in two shading and two irrigation treatments (Mean Value + SE) (NB. the letters on the graph denote difference from the transformed values)

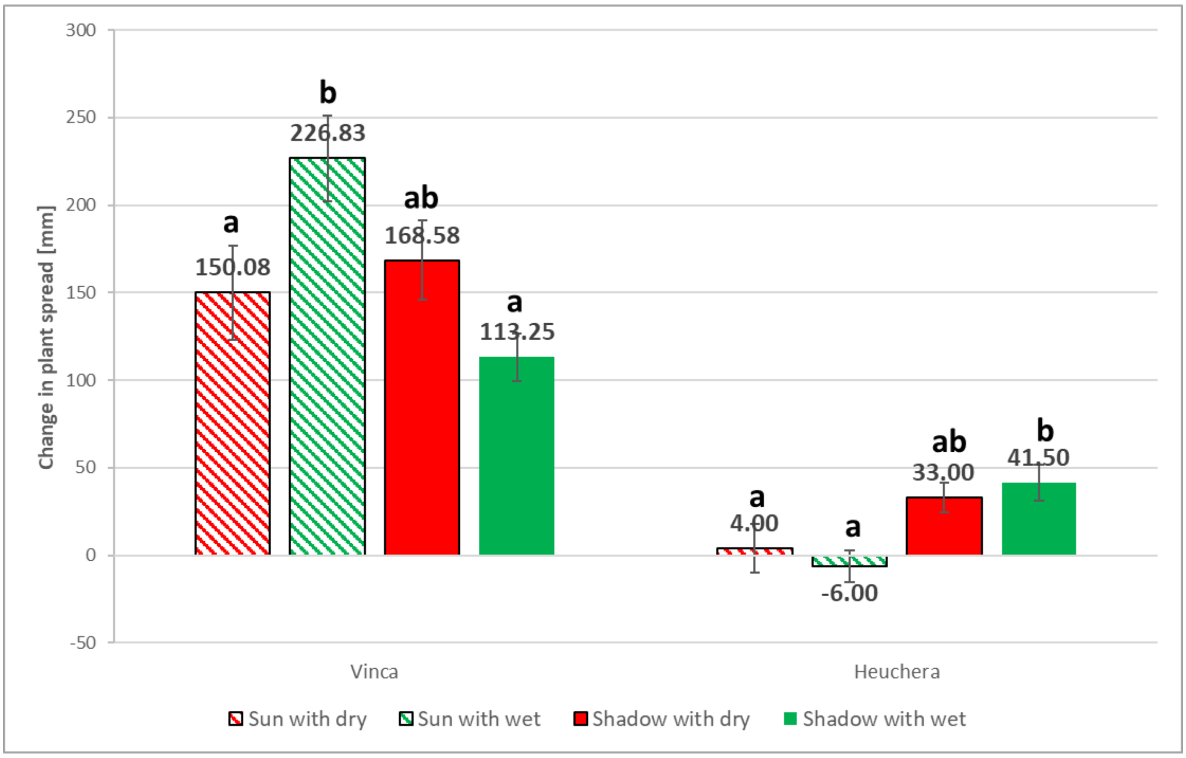

Figure 5.15 The mean change in plant spread in Day 90 (two plant species in two shading and two irrigation treatments (Mean Value + SE) (NB. the letters on the graph denote difference from the transformed values)

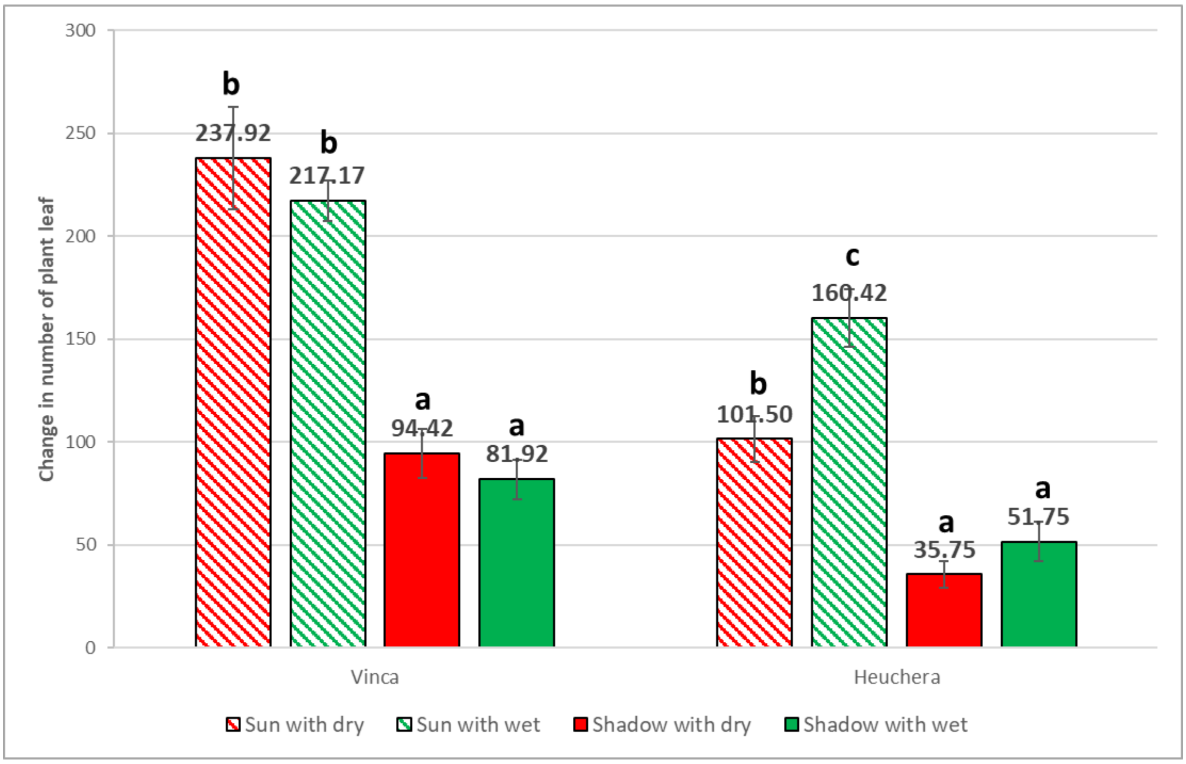

Figure 5.16 The mean change in plant leaf number in Day 90 (two plant species in two shading and two irrigation treatments (Mean Value + SE) (NB. the letters on the graph denote difference from the transformed values)

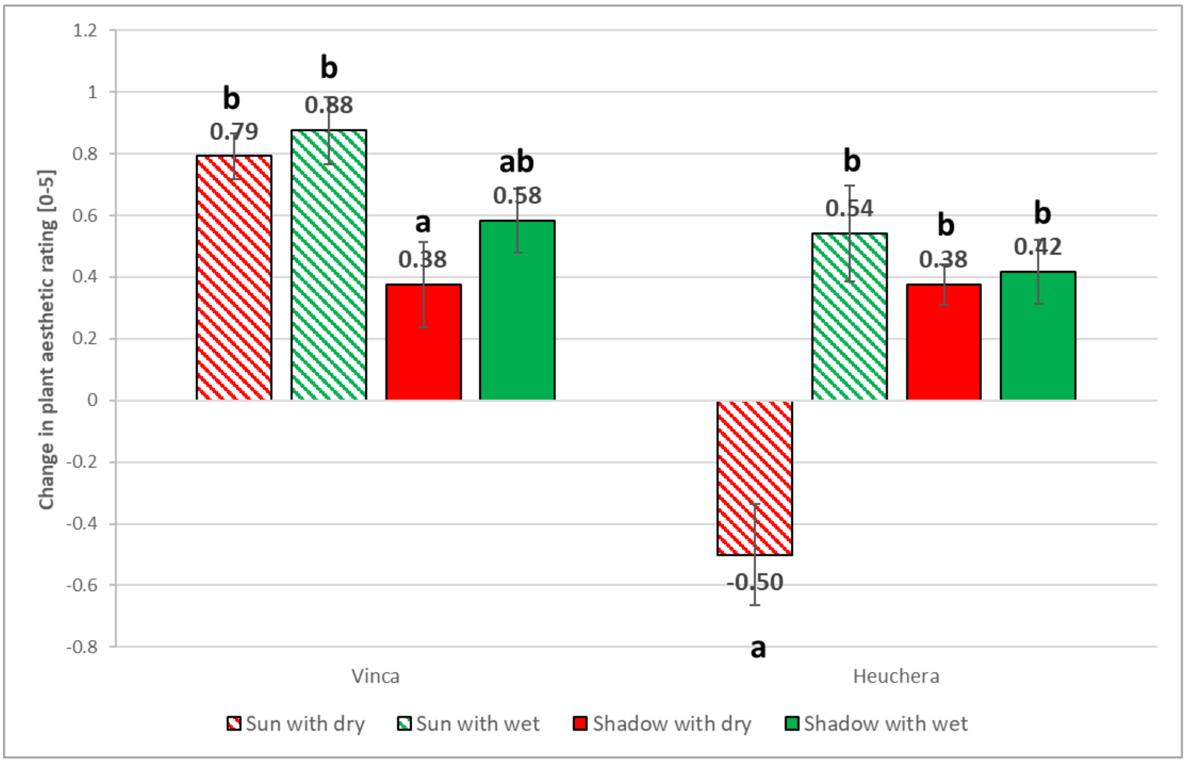

Figure 5.17 The mean change in plant aesthetic rating in Day 90 (two plant species in two shading and two irrigation treatments (Mean Value + SE) (NB. the letters on the graph denote difference from the transformed values)

5.3 EXPERIMENT DISCUSSION

Overall, *Vinca* grew better in terms of plant height (Fig. 5.14), plant spread (Fig. 5.15) and leaf numbers (Fig. 5.16), compared to *Heuchera*; the contrast is especially striking considering the fact that there is a condition in which the plant height of *Vinca* has increased on a positive rate whereas that of *Heuchera* has decreased (Fig. 5.14). Given that a bigger size and more leaves generally lead to a higher rating in aesthetics, *Vinca* seems the more resilient and adaptable of the two taxa to different stress conditions. Based on these results this taxon was able to tolerate the often-adverse conditions associated with dry conditions in full sun, and dry conditions in the shade. In contrast, *Heuchera* marginally tolerates the shadow environment better than the sun.

The light treatments had a greater effect on plant growth than the irrigation in the end of Exp 3. Sunlight has significantly promoted the development of the number of plant leaves, while changes of the plant size were more noticeable under the shadow environment. However, even significant difference caused by irrigation treatments appeared in plant spread of *Vinca* and plant leaf number of *Heuchera* in the sun group only, and the wet treatment was more advantageous for both species in most cases.

Vinca showed a tendency for greater plant spread (1.3 times greater) and more new leaves (2.6 times greater), which was positively related to sun exposure. This correlation explains the relatively higher aesthetic rating for *Vinca* under the sun compared to that in the shadow condition. In the visual aspect, *Vinca* grew impressively dense with short light yellow-green leaves in sun, compared with in shadow. *Vinca* in shadow environment, in order to gain more sunlight, mainly increased the leaf size instead of growing more new leaves. The large size and medium size leaves accounted for 19.6% and 71.4% separately when plants were in shadow, which greater than 13.2% large size and 78.6% medium size leaves in the sun (Table 5.2). The small size leaves had limited effect on the appearance of plants, and even the percentage of small size leaves was similar under the two different shading treatments. In terms of the irrigation treatments (dry vs. wet), the most obvious observation is that wet treatment leads to a significantly broader spread of *Vinca* in the sun treatment. The advantage of wider plants (wet treatment) does not result in more new leaves, however, while the dry treatment does (average 237.92 per plant in dry than that average 217.17 in the wet, Fig. 5.16). In contrast, no significant difference has been found between different irrigation treatments under the shadow environment. In addition, irrigation treatments did not change the ratio of plant leaf sizes. On a whole, the growth of *Vinca*'s height shows no significant difference across different treatments, and any growth was mostly expressed as lateral extension and new leaves.

Heuchera, on the other hand, shows a pattern that is quite distant from *Vinca* in terms of the shading treatments. For *Heuchera*, the sun condition leads to dieback in the plant height. While more new leaves do emerge under the sun (average 130.96 leaves in sun group while average 43.75 leaves in the shadow group, Fig. 5.16). However, most leaves tend to be lighter yellow and even a few were wilted in the sun, especially under the dry treatment, which significantly reduced aesthetic rating due to those lower quality leaves. In contrast, shadow environment leads to relatively higher leaf quality and proportion of large size leaves (average 49.3% large size and 11.8% small size leaves per plant in shadow than that average 43.1% of large size and 16.9% of small size leaves in the sun, Table 5.3). Which echoes the same tendency as *Vinca*, the larger size of leaves often found in the shadow condition allows for acceptable aesthetics. And this result supports the third hypothesis, which large leave plants will perform better in the shadow environment. On a whole, the sunlight resources could be considered as a disadvantageous factor if the aim of the treatment is to achieve an acceptable aesthetics and acceptable aesthetics. Plants that had natural spread and creamy yellow leaves in the shadow group gave a stronger impression than that curly light-colour leaves in the sun, even if there was a disadvantage in the quantity.

Comparing the growth of those two species, plants grown in the Sun will not always grow more strongly than those in Shadow (the first hypothesis). Although *Vinca* showed greater growth in both plant size and number of leaves in the sun group, the growth of *Heuchera*, however, cannot support this hypothesis due to smaller plant size in the sun. Even *Heuchera* gained more leaves in the sun, such number of leaves not only had limited benefit to plant size or shape, but also caused negative changes in aesthetic rating due to the low quality (e.g., curly and light-colour) especially under sun and dry treatment.

In terms of the irrigation treatments (dry vs. wet) for the growth of two species, there is generally no statistically significant difference in the plant growth between different irrigation treatments in the same shading treatment, only two cases (*Vinca*'s spread in sun and *Heuchera*'s leaves in sun. Figs 5.15 and 5.16) had been observed. This finding does not support the second hypothesis. Even so, plants growing under the wet treatment have visually greater plant size and quality than those under the dry. For instance, the difference of *Vinca*'s spread between the dry (150.1 mm) and the wet (226.8 mm) is hard to ignore although there is no statistical difference between them. Considering the plant growth under different treatments, the irrigation advice is given in Table 5.7.

Table 5.7 The optimal and economic irrigation treatment for *Vinca* and *Heuchera* in Experiment 3

PLANT SPECIES	Group of Sun (OPTIMAL)	Group of Sun (ECONOMIC)	Group of Shadow (OPTIMAL)	Group of Shadow (ECONOMIC)
Vinca major 'Variegata'	Wet treatment	Dry treatment	Dry treatment	Wet treatment
Heuchera 'Marmalade'	Wet treatment	Wet treatment	Wet treatment	Dry treatment

5.4 CONCLUSION

Experiment 3 shows that the effect of shading treatment on plant growth is generally greater than the irrigation treatment in most cases. However, there is no solid evidence to support that the plants always grow better in the Sun group than in the Shadow in LWS environment. There is still a clear trend that both plant species in the sun group gain a significant more number of leaves compared to the shadow group both in statistical and visual aspects, but no such trends are present in the changes of plant height and spread. Plants with relatively high drought-tolerance such as *Vinca* tend to increase their spread rather than height when they have a preferable sunlight environment.

In terms of the change in plant aesthetic rating, it has been strongly affected by both shading and the irrigation treatments at the same time. For different irrigation treatments, the change of aesthetic rating is greater in the wet than the dry treatment. However, the aesthetic changes of plants under different shading treatments are more complex. Although the aesthetic rating in the sun group is significantly greater than that in the shadow group, *Heuchera* in the dry treatment was the exception that showed a decrease. Therefore, it is not certain that plant in the sun group is better than that in the shadow group in terms of changes in aesthetic rating.

Although different plant species have different growth rate under different shading and irrigation treatments, it is the plant species with greater growth capacity that tend to grow better in the LWS environment.

Key Points in Experiment 3

- Shading treatment had a greater effect on plant growth than irrigation treatment.
- The greatest effect of shading treatments on plant growth was the number of leaves and it was the sun treatment that helped plants gain significantly more leaves.
- Although the irrigation treatments had limited effect on plant growth in Exp 3, wet treatment could relieve the stress of sunlight on plant growth to some extent.

CHAPTER 6: OVERALL DISCUSSION AND CONCLUSIONS

Green Walls as a green infrastructure technology has been widely proven to have multiple benefits for urban greening (Wolf, 2012; Cameron et al., 2014; Yuri, 2016; Luan et al., 2017). However, the high cost (especially initial capital investment and long-term maintenance fee) and poor irrigation strategy are the two major factors that prevent its widespread use (Veisten et al., 2012; Perini and Rosasco, 2013; Manso and Castro-Gomes, 2015; Riley, 2017). This research suggests that plant growth (e.g., growth speed, quality) in LWS can be controlled by irrigation system (or controller) through different irrigation treatments. Improved irrigation system could be effective for two primary reasons; 1) reducing the cost of long-term maintenance by slowing down plant growth and thus the frequency that plants need pruning and trimming and 2) higher rates of plant survival and retaining their quality again requiring less expensive maintenance involved in replacing plant specimens. From this research, the best compromise to encourage steady, slow growth and best quality when plants were grown as a single species in the module was as a medium or wet irrigation treatment. (Exp. 1). The pattern was slightly different when mixed species were included in the module (Exp. 2) and the overall recommendation here would be dry treatment in the first phase and the medium treatment in the second phase. Findings of Medl et al. (2018) suggest that low-water environment is more favourable for mixed species to keep plant quality, possibly by reducing the chances of any one species from becoming dominant. In long-term tree experiments, both Hérault et al. (2020) and Zemp et al. (2019) found that planting a species mixture had generally a positive effect on productivity compared to a single monoculture when water resources were limited at certain periods.

6.1 IDENTIFYING IRRIGATION REGIMES THAT PROVIDE THE BEST COMPROMISE (ECONOMICAL REGIMES) IN TERMS OF CONTROLLING GROWTH WITH MAXIMIZING QUALITY (I.E., MINIMIZING LEAF LOSS AND STEM DIEBACK)

One of the aims of this research was to find irrigation strategies that avoided excessive plant growth, whilst still keeping the plants healthy. The assumption being these regimes would optimize water use whilst reducing the degree of maintenance required on the wall. (Essentially maintenance people climbing ladders to trim or replace plants). Thus, the term 'economical regimes' has been used. As such the data has been assessed in a holistic way to attempt to identify the most economic regime for each species.

In single species planting scheme (Exp 1)

A single economic regime was not identified for the 4 species in the cooler UK, during phase 1 (Table 6.1); each species having its own 'preference', e.g., Dry for *Hosta,* Wet for *Heuchera*. During phases 2 and 3, however, most plants responded best to the Wet treatment.

While plants growing in the relatively warmer climate (CN) showed *Vinca* and *Hosta* prefer wet treatment but the *Heuchera* and *Hedera* prefer the medium treatment during the whole three phases (Table 6.1). Over time, growth rates tended to increase in the warmer climate, while it reduced in the cooler UK. The reasons for die-back also varied between the two locations, with it being associated with high temperature in CN in Phase 2, whereas in the UK some dieback was linked to phase 3 in the cooler climate, as plants began to enter dormancy and drop leaves due to natural abscission. Those two findings support that the effects of irrigation treatments will vary, depending on local climate conditions (e.g., CN and UK). The greatest changes on plant growth influenced by irrigation were the plant height for *Vinca* while the plant spread for *Hosta*, *Heuchera*, and *Hedera*. But such changes mainly appeared in the first and second phases. This suggests that the irrigation treatments need to be more carefully designed as temperature rises. Overall, the data also suggests species with relatively higher drought tolerance grew better (*Vinca* grew best while *Hosta* grew at the lowest speed) in the Exp 1 at 2018. This potentially suggests that species with large leaves and high shade-adaptation (e.g., *Hosta*) will perform less well compared to those that can adapt to drier conditions (e.g., *Vinca*).

This phenomenon was also found by Burnett and van Iersel (2008), Garland et al. (2012) and Nemali and van Iersel (2019) who suggested that although lower leaf area (e.g., *Vinca*) reduces photosynthesis and overall carbon gain in plants, the decline in plant photosynthesis under drought environment may be less pronounced due to the lower leaf area keeping the plant in a more favourable state regarding water status (less overall evapotranspiration). Some species such as *Hosta* may allocate relatively more biomass to root development under drought conditions in order to increase water absorbing (Lynch, 2007a, 2007b; Jaramillo et al., 2013) as an effective way of maintaining plant water status and photosynthesis. The capacity to do this though, might be inhibited by the volume of the growing media the roots can explore, i.e. the container or module size, as was possibly the case in this research. Nemali and van Iersel (2019) suggested that container-based bedding plants (e.g., greenhouse, GWs) may not enjoy the advantage of this adaptive response due to the limited space for root growth and water storage. Based on the information from this research on single species, it suggests the economic irrigation strategies employed for *Vinca* be focused on reducing speed of growth (e.g. a medium regime), while for *Hosta* it is focused on improving plant quality and thus a Wet regime, at least during mid-summer (Table 6.1).

Table 6.1 The economical irrigation treatment for different plant species in different cities and phases at single species planting scheme

PLANT SPECIES	2018 EXP 1 (THE SINGLE SPECIES PLANTING SCHEME)					
	SHEFFIELD, UK			JINGMEN, CN		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Vinca major 'Variegata'	Medium	Wet	Medium	Wet	Medium	Wet
Hosta 'Blue Mouse Ears'	Dry	Wet	Wet	Wet	Wet	Medium
Heuchera 'Marmalade'	Wet	Wet	Wet	Medium	Medium	Medium
Hedera helix L.	Medium	Wet	Wet	Medium	Medium	Medium

In mixed species planting scheme (Exp 2)

With the species mixed together in the one module (Exp 2). There was more alignment in results between the UK and China environments for the different species (Table 6.2). For example, *Vinca* often performed well in the Dry treatment. Generally, there is little difference of economical irrigation treatment between two cities in the same phase. This, overall it is recommended that the Dry treatment be chosen for Phase 1, while the medium treatment provides the best compromise for Phase 2. All three species grew greater in the Phase 1 than Phase 2, and better in relatively cooler climates (UK) than relatively warmer climates (CN) in the same phase. This suggests that low temperature can relieve the pressure of plant competition in LWS. This is mainly because the low temperature condition leads to the reduction in plant CO_2 consumption, which influences the photosynthesis and biomass growth (Gifford, 1992; Morison and Lawlor, 1999), and in some cases even inhibits growth (Idso and Kimball, 1989). However, the effect on each different plant species in the mixed group under different irrigation conditions will vary, based on the local climate changes (Table 6.2). The species that is most susceptible to local climate changes is *Heuchera*, followed by *Vinca*, and *Hosta* was least affected (Table 4.15).

The species with the reputed higher drought tolerance (*Vinca*) is the only one out of three species that did not show dieback in mixed species planting, which, however, did occur in 2018 (single species planting scheme). Even so, such data does not provide convincing evidence that some species outcompete others in the mixed species planting scheme, as there was no widespread death recorded, which might be expected to happen when plants experience severe competition. There may be additional reasons for this though. The experiments were relatively short (only 2 months), and the irrigation system is designed to keep the growing media within a stable threshold band.

Table 6.2 The economical irrigation treatment for different plant species in different cities and phases at mixed species planting scheme

PLANT SPECIES	2019 EXP 2 (THE MIXED SPECIES PLANTING SCHEME)			
	SHEFFIELD, UK		JINGMEN, CN	
	Phase 1	Phase 2	Phase 1	Phase 2
Vinca major 'Variegata'	Dry	Wet	Dry	Dry
Hosta 'Blue Mouse Ears'	Wet	Medium	Medium	Medium
Heuchera 'Marmalade'	Medium	Wet	Medium	Wet
Mixed	Dry	Medium	Dry	Medium

Further research is required, but based on this thesis there was no overall evidence that growing plants of different species together in the one module radically altered their potential for survival (See section below).

The influence of direct light (Exp 3)

The effectiveness of living wall systems can be strongly influenced by their orientation and the amount of natural radiation (light) they receive (Cope et al., 2014; Riley, 2017; Dominici et al., 2021). A separate experiment (not in the LWS) was set up to investigate the influence of light on water requirements and plant performance (Exp 3). In terms of light, the light treatments had a greater effect on plant growth than the irrigation. Full sunlight significantly promoted the development of new plant leaves, while interestingly, greatest changes of the plant size were more noticeable under the shadow environment. It is possible that the shadow was changing the relative ratio of red to far-red light (R:FR). A low R:FR ratio leads to a low phytochrome photo-stationary state (PSS) (Sager et al., 1988) and this can encourage shoot extension and etiolation, stem length, petiole and leaf length, but decreases the leaf mass per leaf area (LMA) (Ballaré et al., 1991; Fankhauser and Chory, 1997; Smith and Whitelam, 1997; Evans and Poorter, 2001; Sasidharan et al., 2010). In addition, light intensity also has a great influence on stomatal conductance (Gs). Kang et al. (2017) found that different *Hosta* varieties have similar photosynthetic rate and Gs under the low light condition, but their photosynthetic efficiency showed significant difference with the increase of light intensity.

Overall though the results were surprising in that the shade was not particularly detrimental compared to the sun. Indeed, for *Heuchera* – direct sun and lower irrigation was the most negative treatment combination. It is important to stress however, that the degree of shadow imposed during the experiment, may be different to that experienced by LWS plants in a real urban canyon. For example, the treatment here may have still provided more photosynthetic active radiation than some plants receive in situ in commercial LWS. Further work is required to determine the critical light levels required for strong plant development in LWS.

There was generally no statistically significant difference in the plant growth between different irrigation treatments in the same shading treatment. Even so, the plant size of *Vinca* was relatively large in sunlight while with *Heuchera* it was relatively greater in shadow. The dry reduced plant growth and the wet treatment promoted growth in some extent. Despite the lack of significance, the data in Exp 3 alludes again to the fact that different plant species have different requirements. The 'economical' treatments (best compromise between regulated growth and quality) varied between the two species under test (Table 6.3)

Table 6.3 The economical irrigation treatment for different plant species in different light treatments

PLANT SPECIES	2019 EXP 3 (THE LIGHT TREATMENTS)	
	Group of Sun	Group of Shadow
Vinca major 'Variegata'	Dry treatment	Wet treatment
Heuchera 'Marmalade'	Wet treatment	Dry treatment

6.2 COMPARISONS BETWEEN SINGLE SPECIES AND MIXED SPECIES POPULATIONS

Direct comparisons between the single species groupings and the mixed species groups within the modules (Exp 1 and Exp 2) need to be treated with caution, as seasonal conditions and timings of experimental phases can vary between 2018 and 2019. So it is difficult to compare like for like. Nevertheless, comparisons on growth changes between the two years and trends across species and treatments can inform the advantages and disadvantages of mixing plants together. The following figures (Figs 6.1 to 6.3) summaries the growth and quality changes between the two years.

Taken in the round the data for *Vinca* suggests that plant growth parameters and quality scores are better in the second year compared to the first (Fig 6.1), that is this species was not disadvantaged by being in a mixed grouping in most of the treatment combinations. The trend is less strong for *Hosta* (Fig 6.2), and more strongly influenced by location and phase, but again there is evidence that the plants have not been disadvantaged by being in a mixed grouping, especially within the UK phase 1. If any of the species is disadvantaged by the mixed grouping approach then it is *Heuchera*, but only under very specific circumstances, and not by any great extent, e.g. In China in Phase 1(height, spread and aesthetic scores), China Phase 2 (height and spread) (Fig 6.3). Conversely, this species does well in mixed communities in the UK in both phases.

To conclude, it would appear that under most circumstances, all three species were not disadvantaged by being placed in modules with specimens of other species; these plants coped well with 'community-living'. It needs to be noted that no individual plant died – the ultimate test of plant viability! There is a suggestion though, that when one of these species (*Heuchera*) experiences other forms of stress (e.g., excessive heat – as in China), being in a competitive environment with other species may be detrimental to it. The overall trend (plants here cope with competition) somewhat conflicts with previous work by Blanusa et al. (2009), which showed that *Impatiens* had poorer performance when grown under a low irrigation regime, when a more competitive species (*Petunia*) was added to the growing module.

On the basis of this research, however, the conclusion is that mixed planting in a LWS module is feasible, and different species do not need to be segregated in commercial situations. This study, however, only investigated 4 genotypes and further comparisons are needed in future research.

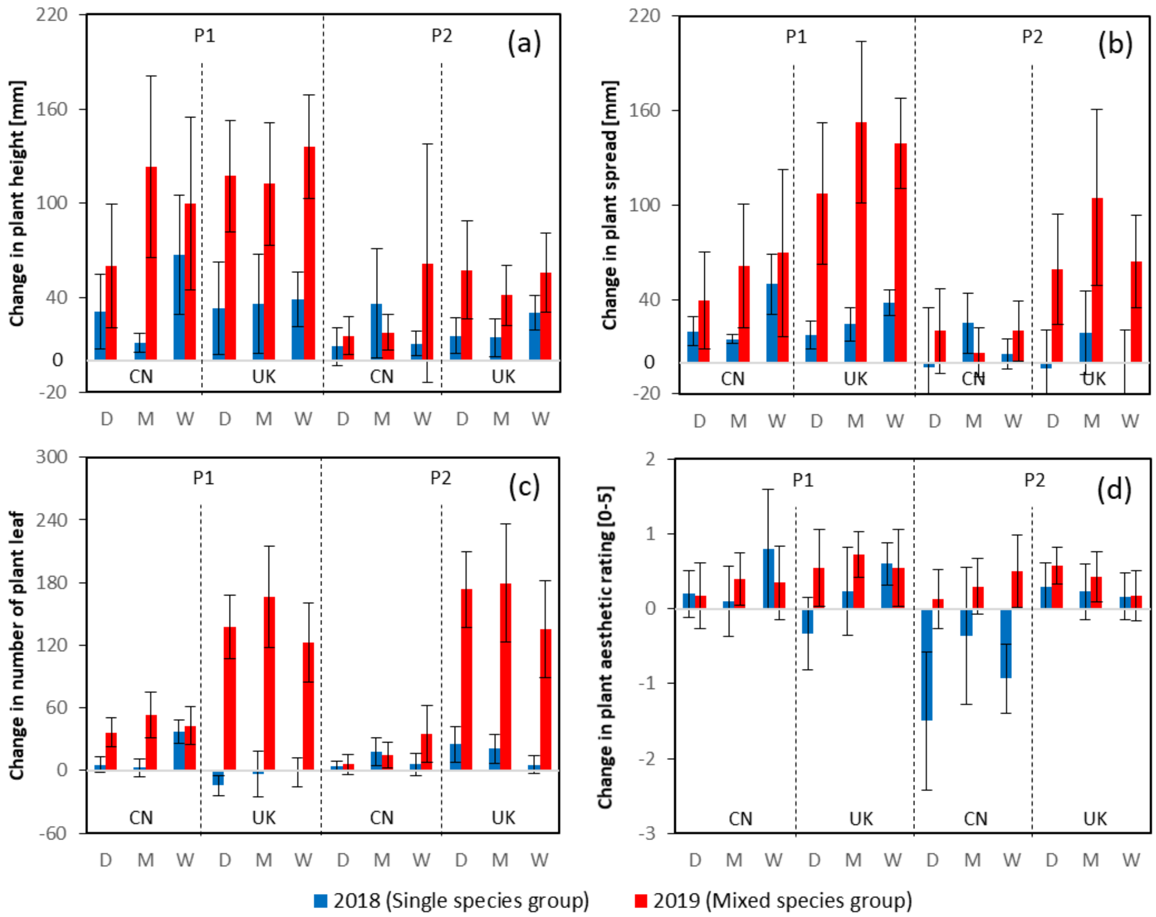

Figure 6.1 The change in *Vinca major* 'Variegata' under different cities and irrigation treatments between 2018 (Exp 1) and 2019 (Exp 2) in Phase (P) 1 and 2 (a. change in plant height, b. change in plant spread, c. change in leaf number, d. change in aesthetic rating). CN = Jingmen, China and UK = Sheffield, UK, and D = the dry treatment, M = the medium treatment and W = the wet treatment (bars represent standard deviation).

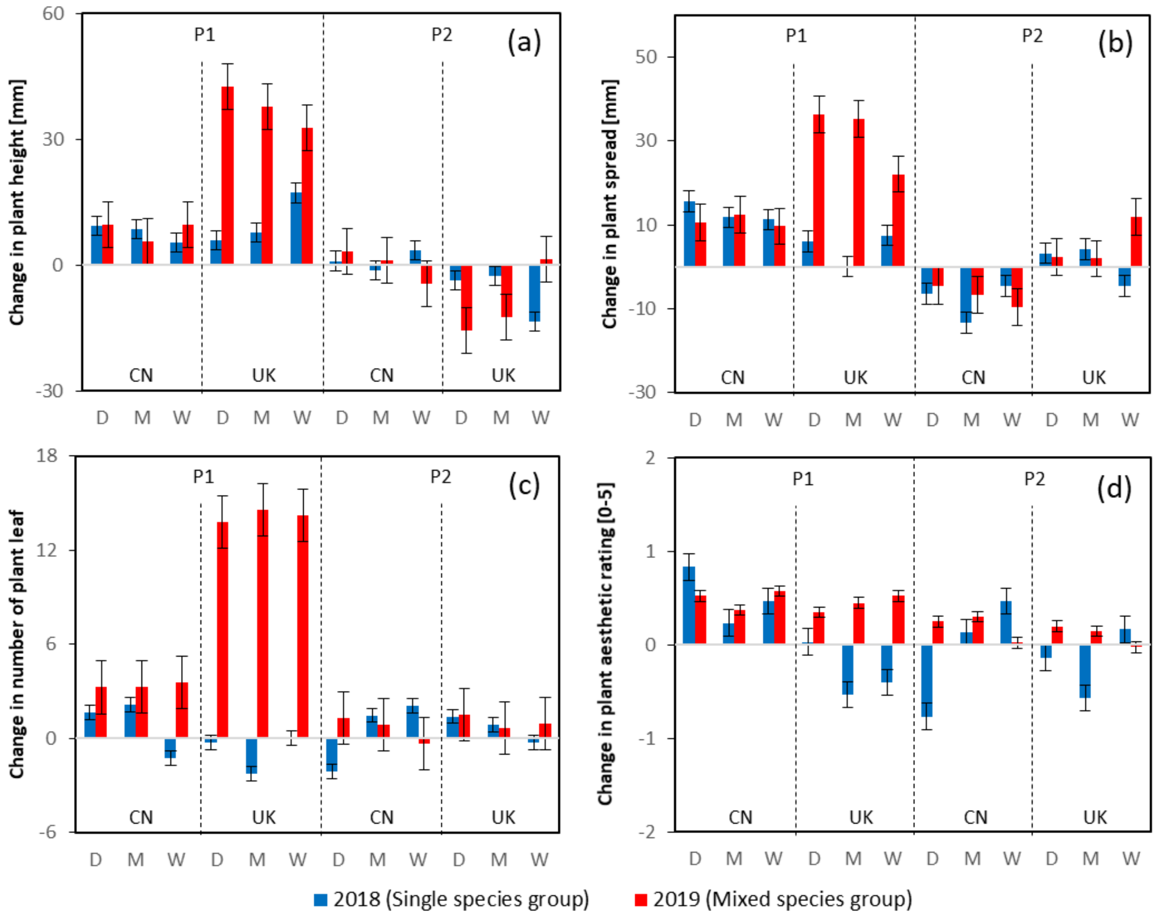

Figure 6.2 The change in *Hosta* 'Blue Mouse Ears' under different cities and irrigation treatments between 2018 (Exp 1) and 2019 (Exp 2) in Phase (P) 1 and 2 (a. change in plant height, b. change in plant spread, c. change in leaf number, d. change in aesthetic rating). CN = Jingmen, China and UK = Sheffield, UK, and D = the dry treatment, M = the medium treatment and W = the wet treatment (bars represent standard deviation).

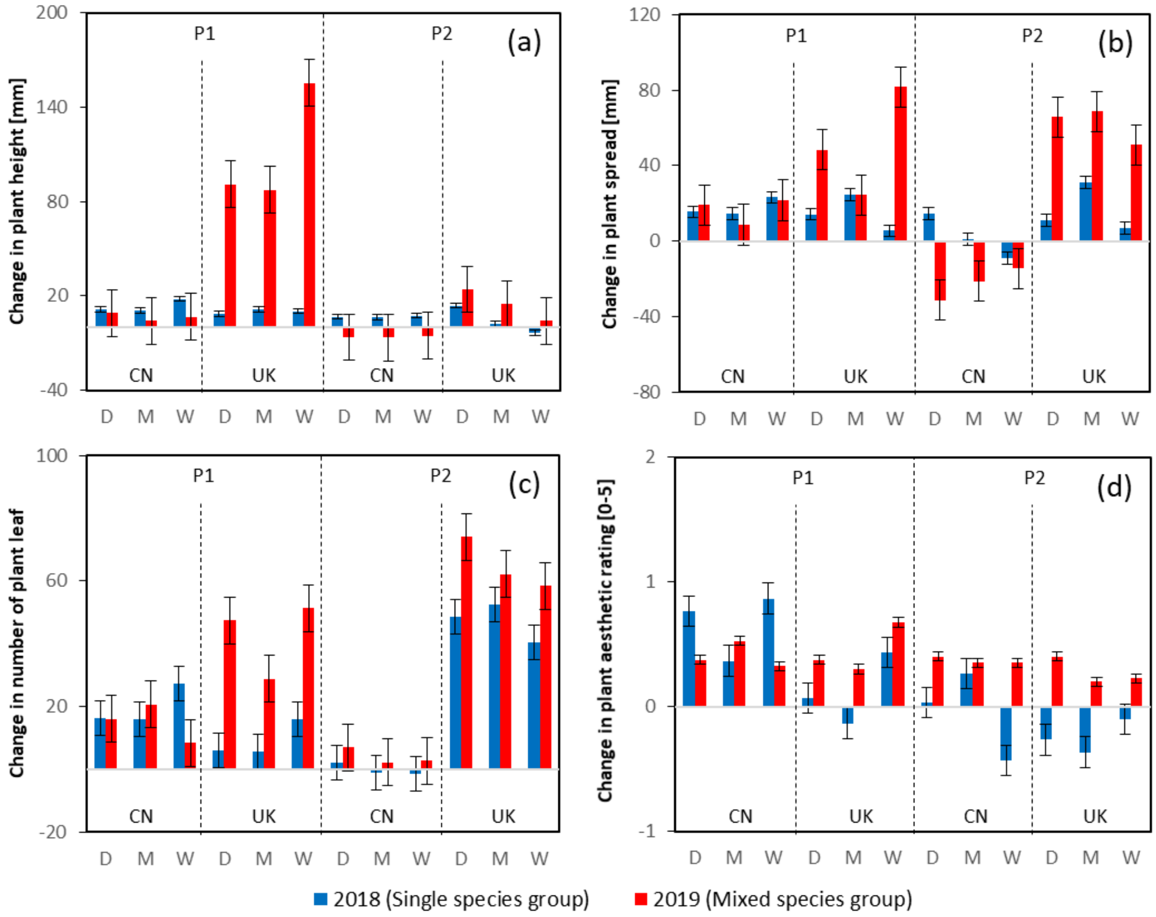

Figure 6.3 The change in *Heuchera* 'Marmalade' under different cities and irrigation treatments between 2018 (Exp 1) and 2019 (Exp 2) in Phase 1 and 2 (a. change in plant height, b. change in plant spread, c. change in leaf number, d. change in aesthetic rating). CN = Jingmen, China and UK = Sheffield, UK, and D = the dry treatment, M = the medium treatment and W = the wet treatment (bars represent standard deviation).

Economic irrigation regimes

The experiment results show that economical irrigation treatments should be changed with time, geography and even planting scheme. Therefore, there is no one best irrigation treatment for all plant species in all phases. Seasons (different phases) have a greater effect on plants growth than irrigation level (soil moisture). This difference was easier to observe in species with relatively higher drought tolerance. In addition, plant growth in LWS is generally greater in Jingmen than in Sheffield in the single species planting scheme and the trend is opposite in the mixed scheme.

Plant's position in LWS does have a certain impact on plant growth, but current LWS experiments cannot prove whether the impact is significant or not. The location of the plant has no statistically significant effects on the plant growth in the LWS within 1-metre height x 0.5-metre width according to this research. Even so, the difference of plant growth between different layers of LWS could reduce under the mixed specie planting scheme. Further experiments are needed to discover the relationship between plant's position and its growth in LWS.

6.3 SUGGESTIONS FROM RESEARCH RESULTS

All results and discussions in this thesis strongly support that the plant growth can be significantly affected by different irrigation levels, similar results also found by Manso and Castro-Gomes (2015), Segovia-Cardozo et al. (2019) and Pérez-Urrestarazu et al. (2014). The irrigation system is an effective technique for controlling excessive plant growth in LWS environment (Medl et al., 2018). Results suggest acceptable aesthetic pleasure is retained whilst achieving relative slowly plant growth, and that better control over irrigation can not only save water, but may also save money by reduced maintenance frequency (Perini and Rosasco, 2013; Bustami et al., 2018; González-Méndez and Chávez-García, 2020; Wilkinson et al., 2021).

All three experiments showed that there is no one universal/common irrigation treatment that could support plant growth in all species at any time in LWS. Climate, meteorological factors (e.g., seasons), planting schemes (e.g., single or mixed) and species are also important factors to design the irrigation treatment. This agree with previous studies e.g. Pérez et al. (2011), Manso and Castro-Gomes (2015) and Kitagawa et al. (2019). Although only 4 species of plants were involved in this experiment, some rules of plant recommendation and irrigation design on LWS for slowing plant growth but maintaining acceptable plant quality can be suggested as follows:

- The LWS location and the exposure level (shading degree) represents two main factors that affect the irrigation treatment design, as they relate climatic condition (e.g., temperature) and sunlight for photosynthesis (Pérez-Urrestarazu, 2021). A higher exposure not only leads to higher evapotranspiration (ET) but also enhance stomatal conductance (Gs) of plants which increases the water consumption (Kang et al., 2017; Lausen et al., 2020; Pérez-Urrestarazu, 2021). In addition, heat reflection from the surrounding environment of LWS also influenced the plant growth as excess heat can increase evaporation (He et al., 2017; Nan et al., 2020).

- The choice of a suitable irrigation frequency also has a great impact on the water use. Short irrigation events and higher frequencies can improve water use efficiency (Pérez-Urrestarazu et al., 2014; Kaltsidi et al., 2020). Although the arrow dripper helps transport water to the plant root, it was found that water easily slipped off the soil surface in the initial stages of the irrigation, especially when the water content of growing media is low. This is also observed Pérez-Urrestarazu et al. (2014) and Kaltsidi et al. (2020) who offers similar recommendations. Although higher irrigation frequencies results in slightly higher drainage volume, but the peak drainage flow is significantly reduced. In addition, Pérez-Urrestarazu (2021) suggests using recirculating irrigation systems and alternative water resource (e.g., rainwater and grey water) which can also improve overall water use. However, such irrigation strategy can work for container-based LWS systems using drought-tolerant species, while is dangerous for felt-based ones (Pérez-Urrestarazu, 2021). In addition, reducing the plant growth rate by irrigation is not always beneficial. Research from Malys et al. (2014)

and Shafiee et al. (2020) show that decreasing the ET will affect the ability of the LWS to mitigate thermal problems in buildings. In essence less evapotranspiration, less water uses and less cooling to the building.

- The performance of growing media (e.g., soil) is also an important factor (Kaltsidi et al., 2020). The drying rate of soil affects the irrigation frequency, and soil with high water saturation capacity can store more water for plants and reduce drainage losses. Suitable growing media can expand the range of plants selection on LWS under demanding climate conditions (Kaltsidi et al., 2020).

- Plants with lower stomatal conductance (Gs) can have their growth controlled more easily via irrigation regimes. This is because that the stomatal state is very sensitive to the change of soil moisture, and Gs thus more strongly affected than any other components in plant water relation (Chaves et al., 2002; Farooq et al., 2009). Plants with higher Gs can maintain higher photosynthetic capacity even in relatively low soil water content by maintaining a relatively higher supply of CO_2, which will lead to faster growth and relatively greater water consumption (Lausen et al., 2020).

- General species suggestions include: 1) Species with extremely strong competitiveness are not advised for LWS. Although these plants can grow and cover the LWS quickly, they will however, lead to higher overall water consumption to keep the plant quality and finally result in more frequent plant trimming. The growth of high-biomass plants will limit their and neighbours ET capabilities (Nagase and Dunnett, 2011; Farrell et al., 2017; Hamann et al., 2018); 2) Species with the large size leaf, characteristics of shade preference and low drought tolerance are not recommended for LWS. Even so, the data presented here suggests such species can survive, if not exactly thriving when growing next to large plants in the dry environment. 3) Succulents and herbaceous perennial plants are recommended over grasses because the health of the plants generally remained stable over the long-time growth (Dvorak et al., 2021). Although it would be interesting to see if succulents survived some of the wetter regimes outlined here. 4) Others such as Lausen et al. (2020) suggest using combinations of high and low transpiration species with succulent roots, shoots or leaves allows for less accurate irrigation treatments, on the assumption at least some species will do well at both the wet and the dry ends of the irrigation spectrum.

The data here indicates the most effective plant growth control can be realised when each plant species within the individual module is supplied with differential irrigation treatments. However, this can lead to extremely high cost and is difficult to achieve. Considering the results discussed previously that the position of plants does not significantly affect plant growth in the small LWS (1m height x 0.5m width), it is recommended that the same species be placed within one container of certain size (no more than 1m height x 0.5m width), sharing one irrigation system (same irrigation treatment). If financial support is guaranteed, further improvement on the irrigation system could be made that each plant has its own individual water valve and container so that each plant can have the most accurate irrigation control in LWS.

Compared with the timer-based irrigation system, the additional cost for sensor-based irrigation control system is primarily in the soil moisture sensor (SMS). If it simply assume that the plant growth rate is only half of the maximum growth rate through such controlled irrigation system in a 10 m^2 LWS, and in this way the additional budget from SMS can be covered after one year (the average maintenance cost for green facades is 5.57 €/m^2/year (4.77 £/m^2/year) (Manso and Castro-Gomes, 2015) and one SM150T costs £145). It is considered competitive from a business perspective, but it is worth noting that this conclusion is only an estimate.

CHAPTER 7: THE FRAMEWORK DESIGN OF SMART IRRIGATION CONTROL SYSTEM FOR LWS

This chapter develops a conceptual framework of Smart Irrigation Control System for LWS (SICS-LWS) based on above research findings. The innovation of such SICS-LWS is the concept model which is not based on the perspective of computers or machine automation, but on the growth of plants as the main factor.

7.1 FRAMEWORK DESIGN

The concept model of Smart Irrigation Control System for LWS (SICS-LWS)

The overall concept model for the Smart Irrigation Control System (SICS) divides into two parts, namely the Software System and the Hardware System (Fig 7.1). The main functions of the Software System are 1) Collecting consumer requirements (Input) and 2) Analysing and designing irrigation strategies (Analysis); while the Hardware System are responsible for 1) Collecting environment data for the Software System and 2) Controlling the water valve according to the command from Software System. The Wireless Module (such as ZigBee) or Wired Module is the bridge to connect these two systems.

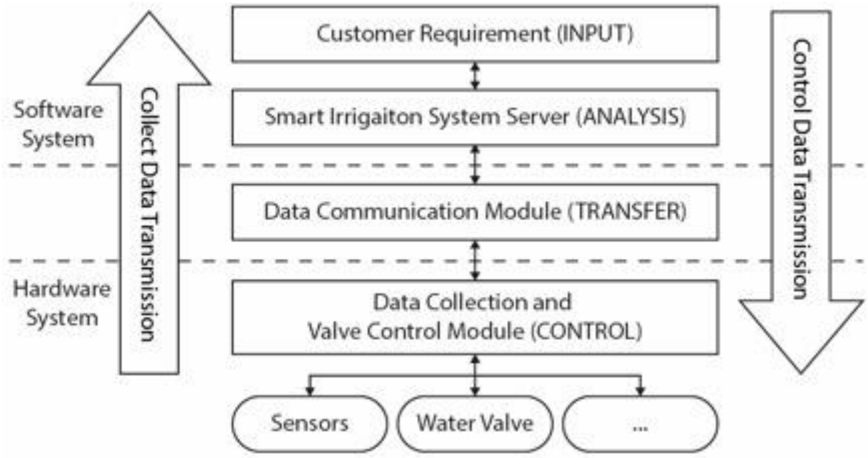

Figure 7.1 The concept model of Smart Irrigation Control System (SICS)

Fig 7.2 shows the concept model of SICS applied in LWS, also called SICS-LWS. Generally, consumer sends the original command (such as Economy Model) to the SICS-LWS. The server in SICS-LWS will collect environment and plant data from Monitoring System and then generate the appropriate irrigation treatment.

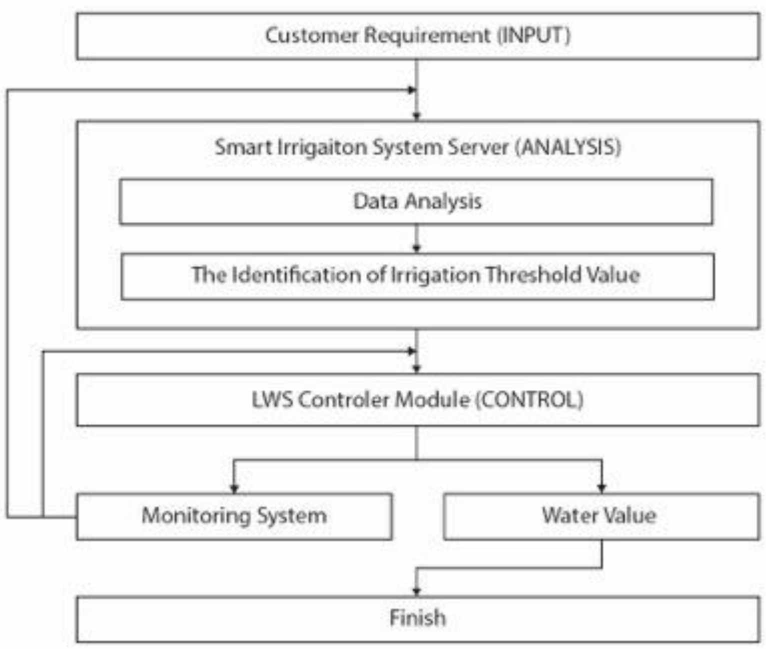

Figure 7.2 The framework of Smart Irrigation Control System for LWS (SICS-LWS)

Details in Smart Irrigation System Server (analysis)

The Data Analysis in the SICS-LWS server (Fig 7.3) firstly determines the plant scheme (i.e., single or mixed group) and then generates the suitable irrigation treatment based on historical records of plant growth by the new innovative computer automatic statistical analysis designed by author (details in Chapter 4.3.3). Plant dormancy is an important factor that can greatly affect the irrigation treatment design and this factor is ignored by the server when it is present.

(When all plants are dormant in the winter – the system may be switched off or put on a low consistent setting – just keeping the substrate moist during the winter).

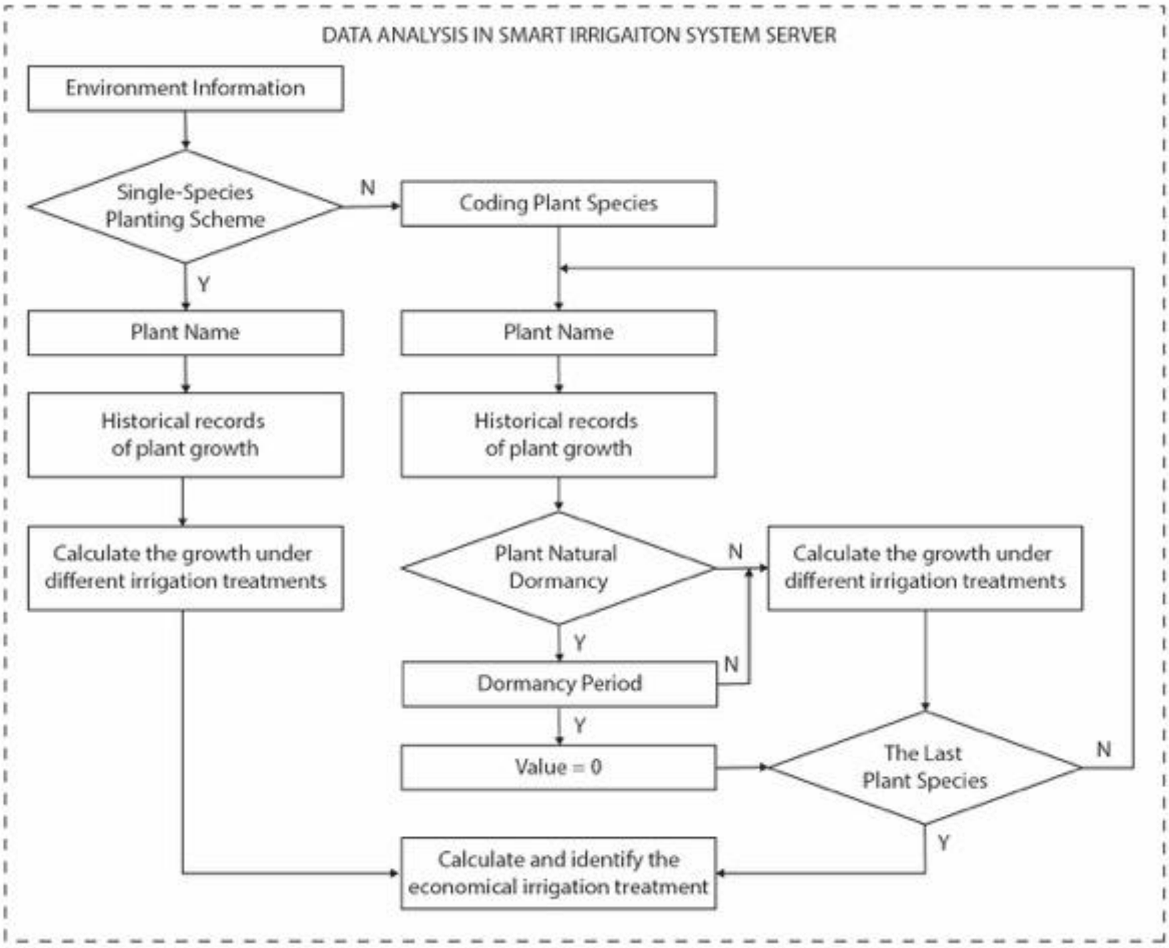

Figure 7.3 The data analysis in the smart irrigation system sever for LWS

The final framework of Smart Irrigation Control System for LWS (SICS-LWS)

Based on all previous work, the final framework of SICS-LWS could be designed as shown in Fig 7.4. There is a brief description of the workflow. The consumer needs to select a model (such as Economy Model, with low plant growth but relatively acceptable aesthetic pleasure) as the main goal that the SICS-LWS needs to achieve. This selected model will be translated as a command and sent to the SICS-LWS Server for further analysis and irrigation plan generation. This plan decision-making is based on the environment information collected by the Monitoring System. Once the irrigation plan is made by the Server, the irrigation command will be sent to SICS-LWS Control Module to set the range of threshold of the water valve. In the meantime, the Monitoring System will keep monitoring the moisture content of growing media (e.g., soil, coco fiber) every 10 seconds so that the system turns on the water valve when the moisture content reaches the minimum threshold value or turns off the water valve when it reaches the maximum. Even if irrigation activities end, the Monitoring System will continuously monitor the environment (e.g., every 600s) and send the relevant data to SICS-LWS sever to ensure the irrigation schedule can be adjusted as the environment changes.

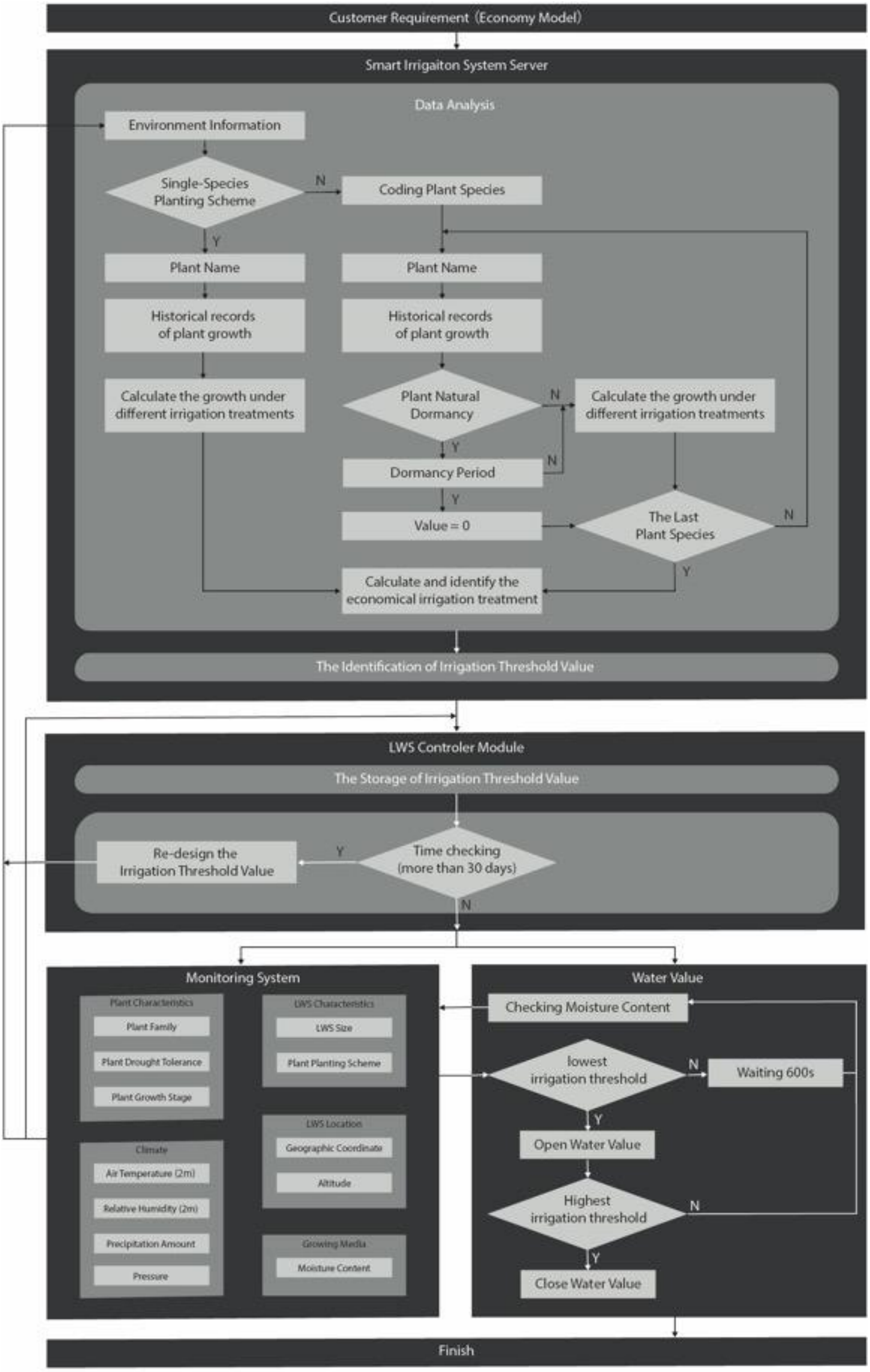

Figure 7.4 The framework of Smart Irrigation Control System for LWS

7.2 RECOMMENDATIONS FOR FURTHER RESEARCH

The benefit of this SICS-LWS as an advanced technology is highlighted by its ability to easily meet customer's pre-setting (e.g., Economical Treatment in this experiment which keeps the plant with acceptable quality but relatively small size changes) adapted to various plant communications, design and a changing environment. Three different LWS experiments in this research show that the climate is a major factor that affects the plant growth in LWS. The temperature, for instance, could promote the plant growth to some extent, but the plant starts wilting when the temperature is over a specifical threshold value which depends on different species. This suggests that more experiments are required to determine the impacts of climatic factors on vegetation growth within LWS and to help meet the worldwide application capacity of such LWS smart irrigation systems.

Although the results of the three experiments here only relate to the Sheffield and Jingmen climates, the data gathered does allow us to determine the implications of thresholds and interactions caused by the climate, for example, excessive temperature or humidity. These aspects can be tested elsewhere and other limitations identified (for example impacts of seasonally low temperature). Thus, further research in other climatic conditions would be useful to finesse the LWS system and overcome potential problems.

The shading degree is another important factor for plant growth, and it could potentially affect the results of GWs research data on different research subjects. Significant difference of plant growth in Experiment 3 shows that *Vinca* and *Heuchera* grow better in the fully sunny environment than in the fully shady environment. But it is unknown how plants will grow under other shading treatments (e.g., half time sunny and half time shady) and plant species. Further research is required in this subject.

The growth pattern of *Hosta* under both single species (Exp 1) and mixed species (Exp 2) planting scheme shows that the mitigation of plant growth can be achieved not only through controlled irrigation, but also through special planting methods. For instance, the wilting of *Hosta* could be relieved by growing near the larger size plant species in the hot climate environment. Therefore, planting methods can also be a potential research subject in the future.

7.3 THE LIMITATION OF RESEARCH

Generally, this research includes three different types of limitations: the limitation of LWS size and plant species, the limitation of research instruments, and the limitation of the application of the Smart Irrigation Control System for LWS (SICS-LWS).

The limitation of LWS size and plant species

Due to the limitation of bench fees, the LWS experiments are only carried out in 1-metre high x 6-metre wide LWSs in two cities with 4 different plant species to explore the effect of irrigation treatments on plant growth. This might have limited the numbers of plant species involved in this research, and therefore the adequacy of the data obtained from the plant growth is limited. For instance, although the results discussion of this research does not consider the position effect in LWS as it will not significantly affect the vegetation growth on different level of LWS in this experiment, it does not mean that plants in LWS greater than 1 m in height are not affected by such effects. Therefore, the results of this research about the prototype model of the SICS-LWS is applicable only to LWS shorter than 1 metre. Application in taller LWS needs more supporting experiments.

The limitation of research instruments

As claimed in Chapter 2, the research methods adopted for this research also have limitations, such as the data veracity and the aesthetical rating of observer bias. However, based on the full understanding of such limitations, some methods have been applied to reduce the limitations caused by the research instruments. Such work includes using the white balance correction in Adobe Photoshop to resolve the colour problems and making the aesthetic rating judgement three times at the same day. However, there could still be some potential limitations in the experiment.

In addition, different components of growing media lead to different rates of water movement. This may cause deviation between measured value and real value. However, this deviation could be reduced by more analysis of the growing media in LWS in the future.

The limitation of the application of the SICS-LWS

As specified above, this research only selected two cities and one type of LWS product (Treebox Limited Company, UK) to explore the concept of the smart irrigation system. This may affect the extensive application of SICS-LWS since the data source is limited. However, this limitation has been reduced by rational selection of the city for this study. Moreover, it is a pioneering design, the significance of the experiment lies more in the enlightenment itself rather than its practical application. Nonetheless, more experiments on different cities are necessary in the future.

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APPENDIX

The calculation of the economical irrigation treatment

There are two examples of calculation of the economical irrigation treatment on both single and mixed planting scheme in Appendant.

Table. 1 The case study of the calculation of the economical irrigation treatment

NUMBER	CITY	PLANTING SCHEME	PLANT SPECIES	TIME
Case 1	Sheffield	Single	*Vinca major* L.	01/08/2018
Case 2	Jingmen	Mixed	*Vinca major* L. *Hosta* 'Blue Mouse Ears' *Heuchera* 'Marmalade'	01/08/2019

Case 1: single plant species planting scheme

There were total of 15 *Vinca Major* L. grown in the LWS (1m height x 1m width x 0.3m thick) in Sheffield, UK at 1th August 2018.

The set of the changes in plant height is **H** = {0.97, 0.52, 1.70};

The set of the changes in plant spread is **S** = {-0.46, 0.89, -0.57 };

The set of the changes in plant leaf number is L = {18.27, 16.20, 7.20 };

The set of the changes in plant aesthetic rating is **a** = {0.50, 0.30, 0.33 };

The set of the actual value of plant aesthetic rating is **A** = {4.40, 4.27, 4.27}.

Among them, the first, second, and third data in the set are the mean values of plant grown in the dry, medium and wet treatment respectively.

A: Judge the changes in plant aesthetic rating and actual value of plant aesthetic rating

According to the value of actual and changes in plant aesthetic rating, the a1=1, a2=1, a3=1, A1=1, A2=1, A3=1.

B: Calculating the mean value of height µH, mean spread µS, mean number of leaves µL:

$$\mu H = \frac{\sum_{i=1}^{n} hi}{n} = \frac{0.97 + 0.52 + 1.70}{3} = 1.06$$

$$\mu W = \frac{\sum_{i=1}^{n} wi}{n} = \frac{-0.46 + 0.89 - 0.57}{3} = -0.05$$

$$\mu L = \frac{\sum_{i=1}^{n} hi}{n} = \frac{18.27 + 16.20 + 7.20}{3} = 13.89$$

Calculating the sample standard deviation of the changes in plant height (SH), plant spread (SS), plant leaf number (SL):

$$SH = \sqrt{\frac{\sum_{i=1}^{n}(hi - \mu H)^2}{n-1}} = \sqrt{\frac{(0.97 - 1.06)^2 + (0.52 - 1.06)^2 + (1.70 - 1.06)^2}{3-1}} = 0.60$$

$$SS = \sqrt{\frac{\sum_{i=1}^{n}(si - \mu S)^2}{n-1}} = \sqrt{\frac{(-0.46 + 0.05)^2 + (0.89 + 0.05)^2 + (-0.57 + 0.05)^2}{3-1}} = 0.81$$

$$SL = \sqrt{\frac{\sum_{i=1}^{n}(li - \mu L)^2}{n-1}} = \sqrt{\frac{(18.27 - 13.89)^2 + (16.20 - 13.89)^2 + (7.20 - 13.89)^2}{3-1}} = 5.88$$

Calculating the Z-score normalisation value of plant growth under different irrigation treatments based on the following formula:

$$Z = \frac{x - \mu}{S}$$

Where Z is the data after standardization, X is the imported data, μ is the data mean, and S is the sample standard deviation.

$$ZH1 = \frac{h1 - \mu H}{SH} = \frac{0.97 - 1.06}{0.60} = -0.15$$

$$ZS1 = \frac{s1 - \mu S}{SS} = \frac{-0.46 + 0.05}{0.81} = -0.51$$

$$ZL1 = \frac{l1 - \mu L}{SL} = \frac{18.27 - 13.89}{5.88} = 0.74$$

$$ZH2 = \frac{h2 - \mu H}{SH} = \frac{0.52 - 1.06}{0.60} = -0.9$$

$$ZS2 = \frac{s2 - \mu S}{SS} = \frac{0.89 + 0.05}{0.81} = 1.16$$

$$ZL2 = \frac{l2 - \mu L}{SL} = \frac{16.20 - 13.89}{5.88} = 0.39$$

$$ZH3 = \frac{h3 - \mu H}{SH} = \frac{1.70 - 1.06}{0.60} = 1.07$$

$$ZS3 = \frac{s3 - \mu S}{SS} = \frac{-0.57 + 0.05}{0.81} = 0.67$$

$$ZL3 = \frac{l3 - \mu L}{SL} = \frac{7.20 - 13.89}{5.88} = -1.14$$

C: Calculation of the Value of Balance Model under different irrigation treatments:

$$Qi = \frac{ZHi + ZSi + ZLi}{Ai \times ai}$$

Where Qi is the sum of Z-score standardised value of plant growth (Value of Balance Model) under irrigation treatment i; ZHi is the Z-score standardised value of changes in plant height under irrigation treatment i; ZSi is the Z-score standardised value of changes in plant spread under irrigation treatment i; ZLi is the Z-score standardised value of changes in plant leaf number under irrigation treatment i; Ai is the transformed data by actual value of plant aesthetic rating under irrigation treatment i; ai is the transformed data by changes in value of plant aesthetic rating under irrigation treatment i.

$$Q1 = \frac{ZH1 + ZS1 + ZL1}{A1 \times a1} = \frac{\frac{h1 - \mu H}{SH} + \frac{s1 - \mu S}{SS} + \frac{l1 - \mu L}{SL}}{A1 \times a1} = \frac{\frac{0.97 - 1.06}{0.60} + \frac{-0.46 + 0.05}{0.81} + \frac{18.27 - 13.89}{5.88}}{1 \times 1} = 0.09$$

$$Q2 = \frac{ZH2 + ZS2 + ZL2}{A2 \times a2} = \frac{\frac{h2 - \mu H}{SH} + \frac{s2 - \mu S}{SS} + \frac{l2 - \mu L}{SL}}{A2 \times a2} = \frac{\frac{0.52 - 1.06}{0.60} + \frac{0.89 + 0.05}{0.81} + \frac{16.20 - 13.89}{5.88}}{1 \times 1} = 0.65$$

$$Q3 = \frac{ZH3 + ZS3 + ZL3}{A3 \times a3} = \frac{\frac{h3 - \mu H}{SH} + \frac{s3 - \mu S}{SS} + \frac{l3 - \mu L}{SL}}{A3 \times a3} = \frac{\frac{1.70 - 1.06}{0.60} + \frac{-0.57 + 0.05}{0.81} + \frac{7.20 - 13.89}{5.88}}{1 \times 1} = -0.71$$

According to the calculation, Q3 < Q1 < Q2. The Q3 (i.e., the wet treatment), therefore, is the treatment that for economic irrigation treatment requirements for *Vinca* that growing in Sheffield between 01/08/2018 to 01/09/2018.

Case 2: mixed plant species planting scheme

There were three plant species include: *Vinca Major* L. (*Vinca*), *Hosta* 'Blue Mouse Ears' (*Hosta*), and *Heuchera* 'Marmalade' (*Heuchera*). Each species has 5 plants and totally 15 plants grown in the LWS (1m height x 1m width x 0.3m thick) in Jingmen, CN at 1th August 2019.

The set of the changes in *Vinca's* height is $\mathbf{H}_{Vinca}$ = {1.60,1.80,6.20};

The set of the changes in *Vinca's* spread is $\mathbf{S}_{Vinca}$ = {2.01,0.63,2.00};

The set of the changes in *Vinca's* leaf number is L_{Vinca} = {5.70,14.40,34.95};

The set of the changes in *Vinca's* aesthetic rating is $\mathbf{a}_{Vinca}$ = {0.13,0.30,0.50};

The set of the actual value of *Vinca's* aesthetic rating is $\mathbf{A}_{Vinca}$ = {4.28,4.48,4.65};

The set of the changes in *Hosta's* height is $\mathbf{H}_{Hosta}$ = {0.33,0.12,-0.45};

The set of the changes in *Hosta's* spread is $\mathbf{S}_{Hosta}$ = {-0.46,-0.68,-0.97};

The set of the changes in *Hosta's* leaf number is L_{Hosta} = {1.30,0.90,-0.35};

The set of the changes in *Hosta's* aesthetic rating is $\mathbf{a}_{Hosta}$ = {0.25,0.30,0.03};

The set of the actual value of *Hosta's* aesthetic rating is $\mathbf{A}_{Hosta}$ = {4.38,4.68,4.23};

The set of the changes in *Heuchera's* height is $\mathbf{H}_{Heuchera}$ = {-0.64,-0.67,-0.54};

The set of the changes in *Heuchera's* spread is $\mathbf{S}_{Heuchera}$ = {-3.13,-2.12,-1.46};

The set of the changes in *Heuchera's* leaf number is $L_{Heuchera}$ = {6.95,2.15,2.55};

The set of the changes in *Heuchera's* aesthetic rating is $\mathbf{a}_{Heuchera}$ = {0.40,0.35,0.35};

The set of the actual value of *Heuchera's* aesthetic rating is $\mathbf{A}_{Heuchera}$ = {4.53,4.50,4.60}.

Among them, the first, second, and third data in the set are the mean values of plant grown in the dry, medium and wet treatment respectively.

A: Judge the changes in plant aesthetic rating and actual value of plant aesthetic rating

According to the value of actual and changes in plant aesthetic rating, the

$a_{Vinca}1=1$, $a_{Vinca}2=1$, $a_{Vinca}3=1$,

$a_{Hosta}1=1$, $a_{Hosta}2=1$, $a_{Hosta}3=1$,

$a_{Heuchera}1=1$, $a_{Heuchera}2=1$, $a_{Heuchera}3=1$,

$A_{Vinca}1=1$, $A_{Vinca}2=1$, $A_{Vinca}3=1$.

$A_{Hosta}1=1$, $A_{Hosta}2=1$, $A_{Hosta}3=1$.

$A_{Heuchera}1=1$, $A_{Heuchera}2=1$, $A_{Heuchera}3=1$.

B: Calculating the mean value of *Vinca's* height μH_{Vinca}, mean spread μS_{Vinca}, mean number of leaves μL_{Vinca}:

Hosta's height μH_{Hosta}, mean spread μS_{Hosta}, mean number of leaves μL_{Hosta}:

Heuchera's height $\mu H_{Heuchera}$, mean spread $\mu S_{Heuchera}$, mean number of leaves $\mu L_{Heuchera}$:

For *Vinca*,

$$\mu H_{Vinca} = \frac{\sum_{i=1}^{n} hi_{Vinca}}{n} = \frac{1.60 + 1.80 + 6.20}{3} = 3.20$$

$$\mu W_{Vinca} = \frac{\sum_{i=1}^{n} wi_{Vinca}}{n} = \frac{2.01 + 0.63 + 2.00}{3} = 1.55$$

$$\mu L_{Vinca} = \frac{\sum_{i=1}^{n} hi_{\ Vinca}}{n} = \frac{5.70 + 14.40 + 34.95}{3} = 18.35$$

For *Hosta*,

$$\mu H_{Hosta} = \frac{\sum_{i=1}^{n} hi_{\ Hosta}}{n} = \frac{0.33 + 0.12 - 0.45}{3} = 0$$

$$\mu W_{Hosta} = \frac{\sum_{i=1}^{n} wi_{Hosta}}{n} = \frac{-0.46 - 0.68 - 0.97}{3} = -0.70$$

$$\mu L_{Hosta} = \frac{\sum_{i=1}^{n} hi_{Hosta}}{n} = \frac{1.30 + 0.90 - 0.35}{3} = 0.62$$

For *Heuchera*,

$$\mu H_{Heuchera} = \frac{\sum_{i=1}^{n} hi_{Heuchera}}{n} = \frac{-0.64 - 0.67 - 0.54}{3} = -0.61$$

$$\mu W_{Heuchera} = \frac{\sum_{i=1}^{n} wi_{Heuchera}}{n} = \frac{-3.13 - 2.12 - 1.46}{3} = -2.24$$

$$\mu L_{Heuchera} = \frac{\sum_{i=1}^{n} hi_{Heuchera}}{n} = \frac{6.95 + 2.15 + 2.55}{3} = 3.88$$

Calculating the sample standard deviation of the changes in *Vinca's* height (SH_{Vinca}), *Vinca's* spread (SS_{Vinca}), *Vinca's* leaf number (SL_{Vinca}); *Hosta's* height (SH_{Hosta}), *Hosta's* spread (SS_{Hosta}), *Hosta's* leaf number (SL_{Hosta}); *Heuchera's* height ($SH_{Heuchera}$), *Heuchera's* spread ($SS_{Heuchera}$), *Heuchera's* leaf number ($SL_{Heuchera}$),

For *Vinca*,

$$SH_{Vinca} = \sqrt{\frac{\sum_{i=1}^{n} (hi_{Vinca} - \mu H_{Vinca})^2}{n-1}}$$
$$= \sqrt{\frac{(1.60 - 3.20)^2 + (1.80 - 3.20)^2 + (6.20 - 3.20)^2}{3-1}} = 2.60$$

$$SW_{Vinca} = \sqrt{\frac{\sum_{i=1}^{n} (wi_{Vinca} - \mu W_{Vinca})^2}{n-1}}$$
$$= \sqrt{\frac{(2.01 - 1.55)^2 + (0.63 - 1.55)^2 + (2.00 - 1.55)^2}{3-1}} = 0.79$$

$$SL_{Vinca} = \sqrt{\frac{\sum_{i=1}^{n} (li_{Vinca} - \mu L_{Vinca})^2}{n-1}}$$
$$= \sqrt{\frac{(5.70 - 18.35)^2 + (14.40 - 18.35)^2 + (34.95 - 18.35)^2}{3-1}} = 15.02$$

For *Hosta*,

$$SH_{Hosta} = \sqrt{\frac{\sum_{i=1}^{n} (hi_{Hosta} - \mu H_{Hosta})^2}{n-1}}$$
$$= \sqrt{\frac{(0.33 - 0.00)^2 + (0.12 - 0.00)^2 + (0.45 - 0.00)^2}{3-1}} = 0.40$$

$$SW_{Hosta} = \sqrt{\frac{\sum_{i=1}^{n}(wi_{Hosta} - \mu W_{Hosta})^2}{n-1}}$$

$$= \sqrt{\frac{(-0.46 + 0.70)^2 + (-0.68 + 0.70)^2 + (-0.97 + 0.70)^2}{3-1}} = 0.25$$

$$SL_{Hosta} = \sqrt{\frac{\sum_{i=1}^{n}(li_{Hosta} - \mu L_{Hosta})^2}{n-1}}$$

$$= \sqrt{\frac{(1.30 - 0.62)^2 + (0.90 - 0.62)^2 + (-0.35 - 0.62)^2}{3-1}} = 0.86$$

For *Heuchera*,

$$SH_{Heuchera} = \sqrt{\frac{\sum_{i=1}^{n}(hi_{Heuchera} - \mu H_{Heuchera})^2}{n-1}}$$

$$= \sqrt{\frac{(-0.64 + 0.61)^2 + (-0.67 + 0.61)^2 + (-0.54 + 0.61)^2}{3-1}} = 0.07$$

$$SW_{Heuchera} = \sqrt{\frac{\sum_{i=1}^{n}(wi_{Heuchera} - \mu W_{Heuchera})^2}{n-1}}$$

$$= \sqrt{\frac{(-3.13 + 2.24)^2 + (-2.12 + 2.24)^2 + (-1.46 + 2.24)^2}{3-1}} = 0.84$$

$$SL_{Heuchera} = \sqrt{\frac{\sum_{i=1}^{n}(li_{Heuchera} - \mu L_{Heuchera})^2}{n-1}}$$

$$= \sqrt{\frac{(6.95 - 3.88)^2 + (2.15 - 3.88)^2 + (2.55 - 3.88)^2}{3-1}} = 2.66$$

C: Calculation of the Value of Balance Model under different irrigation treatments:

$$Qi = \frac{ZH_{Vincai} + ZS_{Vincai} + ZL_{Vincai}}{A_{Vincai} \times a_{Vincai}} + \frac{ZH_{Hostai} + ZW_{Hostai} + ZL_{Hostai}}{A_{Hostai} \times a_{Hostai}} + \frac{ZH_{Heucherai} + ZW_{Heucherai} + ZL_{Heucherai}}{A_{Heucherai} \times a_{Heucherai}}$$

$$Q1 = \frac{ZH1_{Vinca} + ZW1_{Vinca} + ZL1_{Vinca}}{A1_{Vinca} \times \alpha1_{Vinca}} + \frac{ZH1_{Hosta} + ZW1_{Hosta} + ZL1_{Hosta}}{A1_{Hosta} \times \alpha1_{Hosta}} + \frac{ZH1_{Heuchera} + ZW1_{Heuchera} + ZL1_{Heuchera}}{A1_{Heuchera} \times \alpha1_{Heuchera}}$$

$$= \frac{\frac{h1_{Vinca} - \mu H_{Vinca}}{SH_{Vinca}} + \frac{w1_{Vinca} - \mu W_{Vinca}}{SW_{Vinca}} + \frac{l1_{Vinca} - \mu L_{Vinca}}{SL_{Vinca}}}{A1_{Vinca} \times \alpha1_{Vinca}} + \frac{\frac{h1_{Hosta} - \mu H_{Hosta}}{SH_{Hosta}} + \frac{w1_{Hosta} - \mu W_{Hosta}}{SW_{Hosta}} + \frac{l1_{Hosta} - \mu L_{Hosta}}{SL_{Hosta}}}{A1_{Hosta} \times \alpha1_{Hosta}} + \frac{\frac{h1_{Heuchera} - \mu H_{Heuchera}}{SH_{Heuchera}} + \frac{w1_{Heuchera} - \mu W_{Heuchera}}{SW_{Heuchera}} + \frac{l1_{Heuchera} - \mu L_{Heuchera}}{SL_{Heuchera}}}{A1_{Heuchera} \times \alpha1_{Heuchera}}$$

$$= \frac{\frac{1.60 - 3.20}{2.60} + \frac{2.01 - 1.55}{0.79} + \frac{5.70 - 18.35}{15.02}}{1 \times 1} + \frac{\frac{0.33 - 0}{0.40} + \frac{-0.46 + 0.70}{0.25} + \frac{1.30 - 0.62}{0.86}}{1 \times 1} + \frac{\frac{-0.64 + 0.61}{0.07} + \frac{-3.13 + 2.24}{0.84} + \frac{6.95 - 3.88}{2.66}}{1 \times 1} = 1.37$$

$$Q2 = \frac{ZH2_{Vinca} + ZW2_{Vinca} + ZL2_{Vinca}}{A2_{Vinca} \times \alpha2_{Vinca}} + \frac{ZH2_{Hosta} + ZW2_{Hosta} + ZL2_{Hosta}}{A2_{Hosta} \times \alpha2_{Hosta}} + \frac{ZH2_{Heuchera} + ZW2_{Heuchera} + ZL2_{Heuchera}}{A2_{Heuchera} \times \alpha2_{Heuchera}}$$

$$= \frac{\frac{h2_{Vinca} - \mu H_{Vinca}}{SH_{Vinca}} + \frac{w2_{Vinca} - \mu W_{Vinca}}{SW_{Vinca}} + \frac{l2_{Vinca} - \mu L_{Vinca}}{SL_{Vinca}}}{A1_{Vinca} \times \alpha1_{Vinca}} + \frac{\frac{h2_{Hosta} - \mu H_{Hosta}}{SH_{Hosta}} + \frac{w2_{Hosta} - \mu W_{Hosta}}{SW_{Hosta}} + \frac{l2_{Hosta} - \mu L_{Hosta}}{SL_{Hosta}}}{A1_{Hosta} \times \alpha1_{Hosta}} + \frac{\frac{h2_{Heuchera} - \mu H_{Heuchera}}{SH_{Heuchera}} + \frac{w2_{Heuchera} - \mu W_{Heuchera}}{SW_{Heuchera}} + \frac{l2_{Heuchera} - \mu L_{Heuchera}}{SL_{Heuchera}}}{A1_{Heuchera} \times \alpha1_{Heuchera}}$$

$$= \frac{\frac{1.80 - 3.20}{2.60} + \frac{0.63 - 1.55}{0.79} + \frac{14.40 - 18.35}{15.02}}{1 \times 1} + \frac{\frac{0.12 - 0}{0.40} + \frac{-0.68 + 0.70}{0.25} + \frac{0.90 - 0.62}{0.86}}{1 \times 1} + \frac{\frac{-0.67 + 0.61}{0.07} + \frac{-2.12 + 2.24}{0.84} + \frac{2.15 - 3.88}{2.66}}{1 \times 1} = -2.63$$

$$
\begin{aligned}
&Q3\\
&= \frac{ZH3_{Vinca} + ZW3_{Vinca} + ZL3_{Vinca}}{A3_{Vinca} \times \alpha3_{Vinca}} + \frac{ZH3_{Hosta} + ZW3_{Hosta} + ZL3_{Hosta}}{A3_{Hosta} \times \alpha3_{Hosta}}\\
&+ \frac{ZH3_{Heuchera} + ZW3_{Heuchera} + ZL3_{Heuchera}}{A3_{Heuchera} \times \alpha3_{Heuchera}}\\
&= \frac{\frac{h3_{Vinca} - \mu H_{Vinca}}{SH_{Vinca}} + \frac{w3_{Vinca} - \mu W_{Vinca}}{SW_{Vinca}} + \frac{l3_{Vinca} - \mu L_{Vinca}}{SL_{Vinca}}}{A3_{Vinca} \times \alpha3_{Vinca}}\\
&+ \frac{\frac{h3_{Hosta} - \mu H_{Hosta}}{SH_{Hosta}} + \frac{w3_{Hosta} - \mu W_{Hosta}}{SW_{Hosta}} + \frac{l3_{Hosta} - \mu L_{Hosta}}{SL_{Hosta}}}{A3_{Hosta} \times \alpha3_{Hosta}}\\
&+ \frac{\frac{h3_{Heuchera} - \mu H_{Heuchera}}{SH_{Heuchera}} + \frac{w3_{Heuchera} - \mu W_{Heuchera}}{SW_{Heuchera}} + \frac{l3_{Heuchera} - \mu L_{Heuchera}}{SL_{Heuchera}}}{A3_{Heuchera} \times \alpha3_{Heuchera}}\\
&= \frac{\frac{6.20 - 3.20}{2.60} + \frac{2.00 - 1.55}{0.79} + \frac{34.95 - 18.35}{15.02}}{1 \times 1}\\
&+ \frac{\frac{-0.45 - 0}{0.40} + \frac{-0.97 + 0.70}{0.25} + \frac{-0.35 - 0.62}{0.86}}{1 \times 1}\\
&+ \frac{\frac{-0.54 + 0.61}{0.07} + \frac{-1.46 + 2.24}{0.84} + \frac{2.55 - 3.88}{2.66}}{1 \times 1} = 0.92
\end{aligned}
$$

According to the calculation, Q2 < Q3 < Q1. The Q2 (i.e., the medium treatment), therefore, is the treatment that for economic irrigation treatment requirements for mixed species that growing in Jingmen between 01/08/2019 to 01/09/2019.