THE CONSTRUCTION, IRRIGATION AND FERTILISER NUTRITION OF UK GOLF GREENS

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Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

THE UNIVERSITY OF LEEDS

Department of Pure and Applied Biology

March 1994

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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ABSTRACT

A field trial was established of a mixed grass sward grown on three types of golf green construction. These consisted of a topsoil, a sand, peat and soil mixture, and a pure sand. Experimental treatments applied were three levels of irrigation, five of nitrogen fertiliser and two of phosphate. The trial was maintained as a golf green, and artificial wear was applied. Soil moisture deficit predictions by the Meteorological Office conformed with measurements from the soil construction, but the sand-based construction types showed higher deficits. The overall rate of evapotranspiration was around 65 % of predicted values. Pore structure of the sand-based rootzones changed slowly over time, but water infiltration rates fell markedly. The soil constructions showed a reduction in the proportion of larger pore spaces in the top of the profile, and infiltration rates were consistently low. Plant death was associated with both high and low rates of nitrogen fertiliser, low rates of irrigation, and was especially apparent on the sand constructions not receiving phosphate fertiliser. Ingress of the weed species *Poa annua* (L.) occurred mainly on the soil constructions and its rate of ingress was enhanced by increased nitrogen input. Golf ball roll and various aspects of their behaviour after impact onto the turf with simulated 5-iron flight characteristics were measured. Roll length declined with increasing fertiliser rate. Hard greens produced long, high bounces and shallow pitch marks. High rates of both irrigation and nitrogen produced deeper pitchmarks and were associated with the tendency of balls to "screw back". A multi-variate method of classifying the quality of golf greens on the basis of a small number of objective measurements was developed. The classes of greens derived were described in terms of their average visual merit, green "speed", ball behaviour after impact, and the treatment factors which they had received.

Submitted for the degree of Doctor of Phiosophy
March 1994

DEDICATION

To Angela, my family and friends

ACKNOWLEDGEMENTS

Many thanks are due to the Royal & Ancient Golf Club of St Andrews for financial support. Also to Dr Peter Hayes and the Sports Turf Research Institute who contributed to my academic fees and provided the facilities for the research to be carried out.

Special mention is due to my supervisor Dr D. Pilbeam for much helpful advice, and to Dr Andy Newell who initally approached the University on my behalf. I would also like to express my gratitude to Dr Steve Baker, Mr Mike Canaway, Dr Peter Hayes, Dr David Lawson and Mr Dave Moore who provided much constructive criticism of the work during its progress.

Many people have helped out in one way or another. Particular mention is due to my friend and colleague Mrs Carolyn Richards. I would also like to thank M.A. Baines, C. Farman, P.C. Husband, E.C. Kirby, M. Laybourn, R. Lodge, A. Prince, P. Pronczuk, S.A. Richards, B.J. West and J. Wicket for technical assistance and G. Biggs, G. Cook, D. Hollingsworth, and R. Smith for trial maintenance.

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CHAPTER 1 - INTRODUCTION

1.1 GENERAL INTRODUCTION

The first written mention of golf was in 1457 when King James II of Scotland banned the pursuit of the game because it detracted young men from military training. In 1502 the Peace of Glasgow led to its reintroduction and for several hundred years after this the game, and its clubs, evolved, firstly on the coastal dune systems of eastern Scotland at Leith, St Andrews and Musselburgh. The game was introduced to England in 1603 but it was not until 1758 that the first course on Blackheath Common, London, was established, followed in 1818 by the Old Manchester on Kersal Moor. The first English links course at Westward Ho! on the Devon coast was established in 1863.

When a course was laid out the sites of the golf greens (the area around the hole) were determined by the existence of attractive hollows of smooth turf, or of natural plateaux, and by the proximity of suitable hazards (Figure 1.1). The greens were maintained only by the rabbits and sheep. In 1866 the Edinburgh Burgess Society employed a person to "make the holes, look after the flags and mend the turf" (Browning 1955). The "mending of the turf" would probably have meant the replacing of divots since "tees" and "greens" had not then been distinguished. It was not until 1900 that the first green was "planted" at Sunningdale, to the west of London, and the science of greenkeeping may be said to have come about.

Golf is generally considered an expensive hobby. It is played, to a greater degree than football or bowls, by non-manual workers (83%) (Collins 1982), and in Great Britain and Ireland there are 1990 golf clubs with over a million members (Anon. 1989a). An average membership fee is about £400 per year (Colclough 1992 pers. comm.) and the average green fee for non-members is around £10 per round. Approximately 90 million rounds of golf are played in a year throughout the UK and Ireland (Anon. 1976, Collins 1982). As a typical example, the municipal golf course at Hazlehead, Aberdeen was subjected to approximately 45 000 rounds of golf in 1991 (Boocock 1992 pers. comm.). The amount of money spent by the players on the game, not including equipment sales and associated costs, is therefore probably of the order of £0.5 billion per year.

The expensive nature of the sport means that the people who play it expect facilities to be well-maintained, and as one of the main requirements is for turf, the maintenance of turf is of crucial importance. Procedures for the construction and maintenance of golf greens have evolved since 1900 largely through a process of trial and error and the application of a form of "scaled down" agricultural philosophy. However, a golf green is merely an ecosystem, and so improvements in quality brought about by empirical methods could theoretically be understood at a more fundamental level in terms of plant / soil, plant / atmosphere and plant / plant relationships. This task is made easier by the fact that a golf green ecosystem is in fact considerably simpler than most natural ecosystems.

FIGURE 1.1
Charles I, while playing golf on Leith links, receiving the news of the outbreak of the Irish Rebellion. (After Sir John Gilbert 1875).

1.2 SPECIES COMPOSITION OF GOLF GREENS

The swards of the green areas chosen for use in the old golf courses, before 1900, will have consisted of bent-grasses (*Agrostis* spp.) and fescues (*Festuca* spp.). The seedbeds of modern golf greens, in the UK, are usually sown either with a mixture of bent-grasses and fescues, or with pure creeping bent (*Agrostis stolonifera* L.). The two main bent-grass species sold for mixtures for turf use in the UK are *A. castellana* Boiss. & Reut. and *A. capillaris* Sibth. (formerly *A. tenuis* Sibth.). *A. castellana* can be distinguished from *A. capillaris* by its distinctive bluish-green colour and slightly larger ligules. *A. capillaris* is described as a fine-textured, sod-forming perennial of tufted appearance spreading by short rhizomes and sometimes stolons to form close turf (Hanson *et al.* 1969, Hubbard, 1984). Creeping bentgrass, *A. stolonifera*, which is stoloniferous, is sown as the pure species and forms a close turf (Hubbard 1984).

The forms of fescue normally sown are subspecies of red fescue, *Festuca rubra* L.. The most frequently used is *F. rubra* L. ssp. *commutata* Gaud. or Chewing's fescue. This is described as a densely tufted perennial, without rhizomes (Hubbard 1984). Slender creeping red fescue, *F. rubra* L. ssp. *litoralis* (Meyer) Auquier, and bloomed fescue, *F.rubra* L. ssp. *pruinosa* (Hack.) Piper, form loosely tufted patches from long (ssp. *arenaria*) or short (ssp. *pruinosa*), wiry rhizomes, and are also sown on UK golf greens.

Weed species (ie species not chosen for the original seed mixture) are to be found frequently on greens. The range of species is quite narrow, however, and includes only a few non-grasses. The most abundant weed is annual meadow grass (*Poa annua* L.). *P.annua* is able to withstand close mowing, produces small, high-density tillers and regenerates readily from self-sown seed. It is unique among turfgrasses in that it can produce flowers all year round and when mown at less than 5 mm in height. It is, however, less tolerant of stresses such as drought and disease (Peel 1982). It has a slightly more upright growth habit and is a paler green colour than bents and fescues. This means that its presence in a golf green produces an unsightly, patchy appearance and an uneven surface which affects the "true " roll of the golf ball. Its biology and control is much debated and will receive much discussion in this report. Common species which may occur on UK golf greens are listed in Table 1.1.

Turfgrass species can be divided into warm (C - 4 photosynthesis) and cool season (C - 3 photosynthesis) classes (Black 1973). Cool-season species are best adapted to growth during cool, moist periods and commonly have temperature optima of between 15 and 24 °C. Such species are sown on UK golf greens. Warm-season grasses are best adapted to growth during warmer periods, usually lie dormant during colder weather, and have temperature optima of between 27 and 35 °C. Considerable research has been carried out on warm season turfgrasses, some of which will be referred to in this report.

The National Vegetation Classification system for calcifugous grasslands and miscellaneous upland communities in the UK (Anon. 1992a) has no class specifically for golf greens, but the species normally present indicate that the class U1 f (*Festuca ovina - Agrostis capillaris - Rumex acetosella, Hypochoeris radicata* sub-community) may represent the precursor communities of the lowland greens of southern England, and class U4 b (*Festuca ovina - Agrostis capillaris - Galium saxatile, Holcus lanatus - Trifolium repens* sub-community) that of the greens of more montane areas. In both these sub-communities, *F. ovina* may be replaced, to a greater or lesser extent, by *F. rubra*, and the grazing activities of rabbits and / or sheep keep the ground layer height below 15 mm.

BOTANICAL NAME & AUTHOR(S)	COMMON NAME
GRASSES	
Agrostis castellana Boiss. & Reut.	Highland bent *
Agrostis capillaris Sibth.	Browntop bent *
Agrostis stolonifera L.	Creeping bent *
Agrostis canina L. ssp. *montana* Hartm.	Brown bent
Agrostis canina L. ssp. *canina*	Velvet bent
Cynosurus cristatus L.	Crested dog's-tail
Festuca rubra L. ssp. *arenaria* (Osbeck) Syme.	Sand fescue
Festuca rubra L. ssp. *commutata* Gaud.	Chewings fescue *
Festuca rubra L. ssp. *litoralis* (Meyer) Auquier	Slender creeping red f. *
Festuca rubra L. ssp. *pruinosa* (Hack.) Piper	Bloomed fescue *
Festuca rubra L. ssp. *rubra*	Strong creeping red fescue
Festuca ovina L.	Sheep's fescue
Festuca longifolia Thuill.	Hard fescue
Festuca tenuifolia Sibth.	Fine-leaved sheep's f.
Holcus lanatus	Yorkshire fog
Koeleria macrantha (Ledeb.) Schultes	Crested hair grass
Lolium perenne L.	Perennial ryegrass
Phleum pratense L.	Large-leaved timothy-grass
Phleum bertolinii DC.	Small-leaved timothy-grass
Poa pratensis L.	Smooth-stalked meadow-grass
Poa trivialis L.	Rough-stalked meadow-grass
Poa annua L.	Annual meadow-grass
NON-GRASSES	
Juncus bufonius L.	Toadrush
Sagina procumbens L.	Pearlwort
Trifolium repens L.	White clover
Trifolium dubium Sibth.	Lesser yellow trefoil
Veronica officinalis L.	Common speedwell
BRYOPHYTES	
Brachythecium rutabulum (Hedw.)	
Bryum argenteum (Hedw.)	
Bryum caespiticium var. *imbricatum* (Hedw.)	
Ceratodon purpureum (Hedw.)	
Eurhynchium praelongum (Hedw.)	

TABLE 1.1

Common species which may occur on UK golf greens. Those grasses marked * represent those usually sown, either individually or in mixtures.

The managed golf greens of today, like bowling greens, croquet lawns and cricket tables, are classified as very fine turf surfaces (Shildrick 1984). The sward is maintained by frequent mowing at a height of around 5 mm, relaxed to 8 mm in the winter. Due to the intensive nature of most aspects of very fine turf management, it is clear that a study of the ecology of golf greens should draw only lightly from the body of knowledge pertaining to species in grazed, semi-natural grassland.

1.3 GOLF GREEN CONSTRUCTION

During the 20th century, the popularity of the game of golf has increased enormously. This has meant that techniques of course construction have developed which aim to reproduce the surfaces and soil conditions of the early links and lowland heathland courses in areas with widely varying climates and on differing soil types. If these aims are to be realised an understanding of the effects of different construction types and their interactions with environmental and management factors on both the game and the ecology of the green is necessary.

The ecological processes occurring in golf greens may be considered in terms of the influence of edaphic and environmental factors and the interaction of management practices with these processes. Edaphic factors of likely major significance are soil profile and texture and the movement and availability of water and nutrients. The common edaphic characteristics of the greens of the links and heathland courses are the great depths of sand in which the turf grasses grow. On dry lowland heaths, the sandy soils usually overlie a coarse sand sub-stratum (Dimbleby 1962). Golf greens on these soils are generally of a very free-draining nature, and fluctuations in the height of any water table which may be present do not usually affect grass growth at the surface. In order to reproduce the surface characteristics of these soil types, a key element is therefore the maintenance of a freely draining surface.

The texture, structure and profile of the golf green are physical phenomena, the nature of which are largely established when the golf green is first constructed, or its location is first established. Top-dressing with amendment materials such as sand and mechanical procedures, such as spiking or hollow-tining, are normally carried out afterwards and are aimed at maintaining or improving the physical nature of the rootzone. Such procedures cannot be as influential in producing a desirable surface as the selection of the site or the initial rootzone medium and construction type however.

Ward (1983), in a questionnaire survey of UK golf courses, found that 70% of courses were closed due to waterlogging at some stage during 1981, and that greens were more prone to drainage problems than tees or fairways. This suggests that the differing approaches to golf green construction, and/or location, that have been employed are very wide-ranging in their degree of success. Research into the processes taking place and principles involved was therefore considered necessary.

Drainage

A well-drained golf green in the UK should be playable at all times of the year, except during periods of snow or heavy frost. After periods of heavy rain the soil should rapidly drain to a state of "field capacity" (Veihemeyer & Henrickson 1931). That is to say, all the water which could drain away by gravity will have done so. The principles of golf green drainage are targetted towards this goal.

Many golf greens, especially those of clubs established before the turn of the century, have no drains incorporated into them. These rely on the inherent structure of the soil and subsoil to provide the appropriate conditions for drainage.

The simplest form of constructed green is that made by installing pipe drainage into the subsoil, backfilling with gravel and overlaying with topsoil. This approach is necessary where the subsoil has low permeability, such as for inland courses built on clay. Perforated plastic pipe is now most commonly used for this purpose. Patterns of pipe drainage systems and the appropriate depth and spacing of the pipes are dependent, as in agricultural situations, on the soil texture and structure, local hydrological features such as groundwater and surface runoff water, and the climate. In summary, heavy soils require drain spacing of between 2.5 and 4.5 m, and light soils between 7.5 and 12 m. Golf green drains are usually set nearer to the surface than agricultural drains. Depths lie usually between 450 and 900 mm from the topsoil surface. Drainage principles are discussed by Anon. (1975) and their application in golf course situations by Anon. (1992b).

The golf green rootzone - soil texture and structure

The success of the golf green is highly dependent on the nature of the topsoil or rootzone material. In situations where, due to the characteristics of the native topsoil or localised geographical features, adequate drainage and aeration are prevented, the situation may be improved by mixing the soil with sand prior to its being layed down.

Soil amelioration procedures may be assessed by examining the rate of through-flow of surface water or infiltration rate. This may be achieved using a double-ring infiltrometer (Schmidt 1980). Waddington *et al.* (1974) stated that infiltration rate, in most instances, should be used as the primary criterion for evaluating the soil physical conditions of modified turf. In the UK, infiltration rates of pipe-drained golf greens are considered excellent if over 20 mm h^{-1} and good if over 10 mm h^{-1}. If rates are of the order of 5 mm h^{-1}, ponding will occur under conditions of heavy rainfall, but such a green is generally considered to be satisfactory. If the rate is less than 5 mm h^{-1}, problems associated with poor aeration and inadequate drainage arise (Baker & Richards 1993).

Elliot (1971) showed that as the proportion of sand mixed with soil increased from 0 to 100%, infiltration rates on established turf composed of a mixture of turfgrass species increased about 5 times. The type of sand used was extremely coarse however, and the infiltration rates measured were untypically high. After 8 months of simulated golf wear treatment, Baker & Richards (1991) found that infiltration rates of very fine turf grown on 1 : 1 soil : sand mixes was 5 mm h^{-1}, on 1 : 4 mixes 78 mm h^{-1} and on pure sands 398 mm h^{-1}.

A number of specifications have been put forward to indicate the most appropriate particle size distribution, or texture, for amended rootzone media (Skirde 1974, Radko 1974). A specification currently in use in the UK is that sufficient sand should be added such that the final mix contains no more than 20% fines (particles < 0.125 mm diameter), less than 10% silt and clay (particles < 0.05 mm diameter) and less than 5% clay (particles < 0.002 mm diameter) (Baker 1985). The identification of the appropriate type of sand for soil amelioration has been a subject of considerable research interest (eg Adams *et al* 1971, Blake 1980, Baker 1983). The general consensus is that sands for soil amelioration should be of more or less uniform particle size and in the size range 0.1 - 0.6 mm diameter (Adams *et al* 1971).

Compaction and soil structure

The surface of a working golf green is continually subjected to wear by players and machinery. Such wear may be divided into two components, vertical and horizontal. The vertical component of wear is brought about by the weight and frequency of passing of foot and vehicular traffic. This produces compaction of the soil. The horizontal component, produced by the spin of wheels and twist of golf shoes, causes a tearing of the grass.

Compaction, on this scale, produces changes in the soil structure, most notably in the top few centimetres of the profile (Lunt 1956, Letey *et al.* 1966, Baker 1988). The major soil physical changes induced which have been reported are reduced air-filled porosity (Canaway 1978, Schmidt 1980, Baker 1985), increased bulk density (Voorhees *et al.*

1975, Canaway 1978), increased soil strength (Watson 1950) and altered pore size distribution (Carrow 1980, Gibbs & Baker 1989).

The texture of the soil affects its vulnerability to compaction. Baker (1988), using a machine which simulated both the vertical and horizontal components of wear (Canaway 1982), found that rootzone mixes with greater amounts of sand maintained higher values of air-filled porosity and infiltration rate after simulated wear treatment. Mixes with little sand gave very marked reduction in infiltration rate, while pure sands showed a much lesser reduction. The use of coarser sands brought about less change than the finer or less uniform sands.

Schmidt (1980), working with creeping bentgrass (*Agrostis palustris* Huds.) putting green turf grown on a fine, loamy soil, found that air porosity and infiltration rate increased with increasing addition of amendment material consisting of expanded shale or sand. Over an 8 year period, during which different levels of compaction were applied, both air porosity and infiltration decreased, but air porosity reduction was less than the decrease in water infiltration. Compaction also reduced water infiltration rate by a greater amount than its effects on porosity. Schmidt suggested that, with time, the shifting of the mix particles impeded water movement by increasing tortuosity rather than by reducing soil macropore space. In effect, water infiltration may have been limited by the sealing of the surface with time by compaction.

Soil structural phenomena which change due to compaction may affect the growth of turfgrasses by affecting the mechanical restrictions on root growth and the movement, retention and availability of water. The horizontal, tearing components of wear may affect the growth of turfgrasses more directly. In order to study the interactions of plants in a mixed species golf green, it is clearly necessary to consider how these mechanisms influence the growth and interaction of the component species.

Sand-based rootzone mixes

Many of the problems associated with golf green rootzones are related to its textural nature. Since a uniform particle size distribution of between 0.25 to 0.5 mm diameter (medium sand) throughout the rootzone would appear to be the most appropriate rootzone texture, pure sand should provide the optimum physical conditions for golf green turf. The idea of using pure sand as a rootzone for golf greens was first put forward by Bingaman & Kohnke (1970) and subsequently developed by Davis (1973).

Bingaman & Kohnke (1970) specified the type of sand appropriate for golf green use when an impervious layer with drainage elevation control is placed below the sand. They stated that a fine to medium sand should be used, with a mid-range particle diameter of 0.2 - 0.4 mm diameter. Clay, silt and very fine sand should be essentially absent. Under these conditions the problems of inadequate drainage through the rootzone may theoretically be eradicated. Baker (1988) found that after 2 years of simulated football wear, infiltration rates of *L. perenne* turf grown on pure sand ranged from 68 mm h^{-1} for a sand with a range of particle sizes, to 936 mm h^{-1} for a medium - coarse sand (particle size ~ 0.55 mm diameter).

The paradox of sand-based rootzone mixes is that, while infiltration rates may be excellent, a large proportion of the macropore space may be grouped into pore size classes of relatively large diameter. Under these circumstances, the water retention capacity may be low and drought stress may come about more rapidly if water application is limited.

The addition of organic components has some influence on the physical properties of soil or rootzone media and on their capacity to supply water to turf. Peats, when kept continuously moist, can hold 28 - 66% by volume water, compared with only 12 - 16% for sands. For this reason they have been blended with sand for golf green rootzones in order to improve the water retention capacity (Kussow 1987). The United States Golf Association (USGA) rootzone specification (USGA 1960, 1973, 1989) has, throughout its development, always consisted of a blend of sand, soil and organic amendment, partly for this reason.

The USGA specification for golf green construction also endeavours to increase water retention capacity by utilising certain soil physical principles, and these are described below.

The suspended water table principle

In theory, water held in a fine-textured soil resting on a coarse, underlying layer does not move down into the latter until the fine soil is at "field capacity". It forms, in effect, a suspended, or perched, water table (SWT). This is because capillary forces in the fine macropores of the soil hold water until its gravitational force accumulates such that the capillary forces are overcome. The quantity of water which the soil can hold is therefore largely dependent on the macropore diameter, which directly affects the water-retaining capillary forces, and the existence of a clear interface between the upper, fine-textured soil and the lower coarse-textured medium.

The SWT principle is utilised in the construction profile developed by the USGA (USGA 1960) which has since been modified slightly (USGA 1973, Radko 1974, USGA 1989). This construction profile consists of 300 mm of the specified rootzone material, 50 mm coarse sand blinding layer and 100 mm gravel or drainage aggregate. The blinding layer is intended to prevent the loss of the finer rootzone material into the gravel drainage system. The SWT interface is believed to lie between the blinding layer and the gravel drainage layer (Radko 1974).

This form of construction profile is now utilised in order to improve the water retention capacity of both pure sand and amended rootzones. The current USGA specification for golf green construction (USGA 1989) consists of this profile with a rootzone of between 0.25 and 0.75 mm particle diameter (medium to coarse sand). Fine (0.25 - 0.10 mm) and very fine (0.10 - 0.05 mm) sand should be held to a minimum and not exceed 10% of the final mix. Silt (0.05 - 0.002 mm) should comprise no more than 5% and clay (≤ 0.002 mm) not more than 3%. Organic material is added such that values of infiltration and percolation capacity, porosity, bulk density and water retention capacity are arrived at which lie within stipulated ranges.

1.4 WATER RELATIONS AND THE GOLF GREEN

Studies of soil water content and its relationship with soil structure and texture are only of value to the biologist if the results may be expressed in terms related to the life of the plant. If laboratory studies describing soil structure and texture have been carried out, field measurements of soil water content may be related to actual water availability, and hence to the plant responses to water deficits or excesses. Water content may be measured by taking cores from the appropriate depths, weighing, drying and re-weighing (Bascomb 1974). This method is inappropriate however when continuous monitoring over several years is necessary. The use of weighing lysimeters provides a non-destructive means of monitoring changes in soil water content, provided the soil structure within accurately reflects that of the surrounding soil which it represents.

Turfgrass evapotranspiration

The main focus of interest in lysimeter studies of turf water relations has been in the measurement of evapotranspiration (ET). Tovey *et al.* (1969) examined moisture release characteristics and used weighing lysimeters to measure ET of mixed-species turf grown on two types of soil. They showed that a sandy loam soil lost water more quickly, and stabilised at a drier state under increasing tension than a loam soil, and that, when water supply was adequate, ET losses were greatest on the loam soil. This study, and others (eg Aronson *et al* 1987), also examined the relationships between actual and predicted ET, using the Penman formula (Penman 1948, 1963) or other predictive models (eg Olivier 1961).

Feldhake *et al.* (1983) measured turfgrass ET using small-scale weighing lysimeters. They examined the effects of soil composition, mowing height, nitrogen fertiliser applications, shading and grass species on ET. The differences between ET of turf grown on clay soil and on sand-peat mix were confused by problems with irrigation, but a lesser ET rate on clay was suggested. These workers evaluated ET at mowing heights of 20 mm and 50 mm and found that ET was 13% higher with the 50 mm turf. Fry & Butler (1989), using similar apparatus, found that ET from turf mown at 12 mm was higher than that at 6 mm. Feldhake *et al* (1983) suggested that tall grass should be expected to transpire more than short grass since, while no more solar radiation is intercepted per unit area, more advective energy can be intercepted.

Golf green irrigation

Understanding the dynamics of water in a golf green is important if irrigation is to be utilised as a tool of management. Golf green irrigation systems fall into two categories based on the way in which water is delivered to the turf. With the "Cell System" irrigation, and similar systems based on the same principle, the rootzone is completely enclosed in an impermeable membrane. A head of water, of variable height, is maintained within the rootzone by raising or lowering the outfall pipes. While this system is theoretically pleasing, and has been used with some success in places where water supplies are seriously restricted, it does have some drawbacks. Fertiliser, when applied, must be leached into the rootzone from above. Underground irrigation systems do not provide this facility and must therefore be used in conjunction with the most commonly used system, overhead irrigation using sprinklers.

The efficacy of a sprinkler irrigation system may be assessed on the basis of two features. These are the rate of delivery of water to the turf surface and the uniformity of coverage. The output rate of a 360° circling, rotating head sprinkler is of the order of 12 mm h^{-1}. When these are arranged around a golf green, with varying degrees of rotation, a typical average delivery rate to the surface would be about 25 mm h^{-1}. The uniformity of coverage is affected by several factors, chiefly the design of sprinkler and its output rate, the number and arrangement of sprinkler heads and the wind. Meyer & Camenga (1985) discuss the methodology behind the selection of sprinkler systems and Solomon (1990) gives an introduction to the distorting effects of wind on sprinkler distribution patterns.

1.5 TURFGRASS RESPONSES TO SOIL PHYSICAL FACTORS

Since the selection of the most appropriate construction type and rootzone composition is recognised as being crucial to the establishment of high quality greens, much research has been carried out on turfgrass responses to soil physical features. Although the responses of turfgrass species to soil physical phenomena are inextricably linked with nutritional factors, as discussed below, this research may be classified into two groups. The first is concerned with the effects of the mechanical aspects of rootzone media effects on turfgrasses, and the second with the water relations aspects.

Rootzone structural factors

Few studies have been carried out examining the impact of soil physical criteria on individual turfgrass species. Canaway (1985 a,b) measured above ground biomass and shoot density of *L. perenne* grown on both a sand and soil rootzone. Before the onset of wear treatment, at a nitrogen fertiliser rate of 400 kg N ha^{-1} yr^{-1}, total ground cover was approximately equal on the two rootzones. Tiller density was greater on the soil than the sand, but above ground fresh and dry weight were greater on the sand. This would imply that the sand construction produced fewer, larger plants than the soil.

Carrow (1980), applying different levels of compaction to turf mown at 51 mm, found that root growth of *P. pratensis* & *F. arundinacea* was lowest with maximum compaction, while *L. perenne* root production declined and then increased as levels of compaction increased. Carrow suggested that the *L. perenne* response may have been due to enhanced tiller production. The percent root distribution of the three species between depths of 0 - 100 mm and 100 - 200 mm were not, however, influenced by compaction.

Poa annua has long been recognised as a species particularly able to grow on compacted, poorly draining soils (Sprague & Burton 1937, Beard 1970). Youngner (1959) reported that *P. annua* was commonly found in moist situations and suggested that it was able to survive low oxygen levels and was therefore more competitive in compacted soils. Juska & Hanson (1969) found that the mean yield of *P. annua* crowns and clippings were much greater on a silty loam soil than a loamy sand, while root development was reduced on the loamy sand lacking nitrogen. The authors suggested that the silt loam restricted root growth due to greater compaction and reduced aeration, but shoot development appeared to be unrestricted as a consequence.

In contrast, comparing root development on a sandy loam soil of *P. annua, P. pratensis* and *Agrostis palustris*, Wilkinson & Duff (1972) found no differences between the species, nor between their growth on soils compacted to three different bulk densities. This may suggest that the occurrence and success of *P. annua* in golf greens is related more to some factor associated with soil structure and which influences the plant's development, rather than specific soil structural effects on vegetative growth alone.

Different turfgrass species respond differently to simulated wear treatment. Canaway (1978) found that *P. annua* was highly tolerant of wear, a ground cover of 95.4% remaining after 32 passes over 1 month with a wear simulation machine (Canaway, 1976). The grass was mown at 25 mm. *F. rubra* had a ground cover of 33.8% and *A. capillaris* a cover of 20.8% after the same treatment.

The response of *Festuca / Agrostis* mixed swards to different rootzone media maintained as very fine turf and undergoing golf - type wear was examined by Baker (1991). He found that total ground cover declined on topsoil (sandy loam) mixed with increasing quantities of various sands. These effects were most apparent when a medium coarse sand was used, instead of finer textured sands or a sand with a wide range of particle sizes. The cover of *Agrostis* generally increased over the period of wear and was greatest (56%) on the 1 : 1 soil : sand mixes, and least (23%) on pure, medium coarse sand. On the other pure sands, *Agrostis* cover was around 45%. The cover of *Festuca* showed a general decline over the period of wear, but was greatest (46%) on pure sands and least on the 1 : 1 mixes. Over the wear period, the cover of *P. annua* increased from 2% to 12% and showed no clear rootzone composition preferences.

The general tendency of *Agrostis* to displace *Festuca* in mixed swards has been shown by several workers on various rootzone media under various nutritional regimes (Skirde 1974, Woolhouse 1981, Lawson 1987, Colclough & Canaway 1989). Given that *Festuca* has been shown to be marginally more wear - tolerant than *Agrostis* in pure stands (Canaway 1978), this would suggest that the outcome of the interaction between the two species is based on differential responses to each other or to environmental phenomena other than wear.

Turfgrass water use

Differential responses of turfgrass species to water status have been widely studied. Feldhake *et al.* (1983) showed that two warm-season grasses (Bermudagrass - *Cynodon dactylis* L. and Buffalograss - *Buchloe dactyloides* Nutt.) used, on average, 20% less water than two cool-season grasses (Smooth meadowgrass - *Poa palustris* L. and Tall fescue - *Festuca arundinacea* Schreb.). Similar results illustrating the lower water use by warm-season grasses were obtained by Marsh *et al* (1980), Biran *et al* (1981) and Kneebone & Pepper (1982). This result agrees with the expectations for water use by C - 4 plants which generally show a ratio of water use to dry matter production which is less than half that of C - 3 plants (Black 1973).

Green *et al* (1990) and other workers (eg Aronson *et al* 1987, Shearman 1986 and Doty *et al* 1990) have shown that considerable inter- and intra-specific variation in turfgrass ET exists. Green *et al* (1990) found that *F. rubra* ssp. *rubra* had a significantly lower ET rate (7.7 mm day $^{-1}$) than *A. palustris* (10.1 mm day $^{-1}$) and *P. annua* var *reptans* Haushk. (9.8 mm day $^{-1}$). These cool season species were grown in lysimeters and ET was measured using a constant environment simulation chamber (Johns *et al.* 1983) set to induce a high evaporative demand. Grasses were maintained at 50 mm mowing height and the water supply to the roots was held at a level considered non-limiting. Differences in ET were found not to associate with stomatal density, and they suggested that canopy resistance and leaf area were more important factors limiting turfgrass ET.

Kim & Beard (1988) examined ET rates among 11 warm season and 1 cool season turfgrasses and compared them with various morphological characteristics. These they equated with either canopy resistance (shoot and leaf density and leaf orientation) or leaf area (vertical leaf extension rate and leaf width). No convincing association with any morphological feature was found, but leaf width gave the highest correlation with ET. This may suggest that the lower ET rate of *F. rubra* observed by Green *et al.* (1990) may have been due to the narrow, rolled nature of the leaves of this species. Such inter-specific variation in water use rates, though clearly very subtle, are likely to be of significance in controlling the population dynamics of mixed-species, golf green turf.

1.6 FERTILISER USE ON GOLF GREENS

The continual "cropping" of the grasses in a golf green, by frequent close mowing and the removal of clippings, extracts mineral nutrients from the system. These need to be replaced with fertilisers if a "dynamic equilibrium" is to be maintained. The literature concerning the nutrition of golf greens is therefore concerned primarily with the effects of fertilisers on the growth and quality of turf. Most of this work refers to turf grown on individual forms of construction, but some important features emerge regarding the effects of differing rootzone media and water status on turfgrass biology and nutrient requirements. The requirements for nitrogen, phosphorus and potassium have received the most study.

Sources and rates of fertiliser nitrogen for turf

Organic and inorganic forms of nitrogen fertiliser, in both slow-release and normal forms, are all used on very fine turf in the UK (Isaac & Canaway 1987). The most commonly used have nitrogen sources which are primarily the soluble, inorganic ammonium sulphate. It was recognised as long ago as 1912 (Hall 1912) that ammonium sulphate encouraged good growth, colour, texture and uniformity of *Agrostis / Festuca* spp. turf. Since then a stream of workers have arrived at the same conclusions (Oakley 1925, Blackman 1932, Dawson & Greig 1933, Madden 1938, Levy 1957, Escritt & Lidgate 1964, Escritt & Legg 1969, Skogley 1967, Robinson *et al.* 1977, Pepper & Kneebone 1984).

Most inorganic fertilisers, and ammonium sulphate in particular, cause soil acidification and loss of exchangeable cations (Wild 1988a). Excessive use of these fertilisers on very fine turf has therefore been shown to produce detrimental effects such as a less vigorous sward, increased susceptibility to injury, weed and moss invasion and the rapid development of thatch (Sprague & Evaul 1930, Dawson & Greig 1933, Escritt & Lidgate 1964, Skogley 1967, Schmidt 1975, Opitz von Boberfeld *et al.* 1979, Robinson 1980, Murphy 1983).

In order to overcome the difficulties imposed by the acidifying nature of inorganic fertilisers, combinations with alkaline and/or organic nitrogen sources have been tried. Escritt & Lidgate (1964) found that a mixture of ammonium sulphate with hoof and horn meal or dried blood, in the ratios 3 : 1 and 6 : 1 respectively, maintained a fine, weed - free *A. castellana / F. rubra* ssp. *commutata* turf with good colour and improved drought resistance. Levy (1957) found that an ammonium sulphate and sodium nitrate (3 : 1) mix produced similar results on *A. capillaris / F. rubra* ssp. *commutata* turf.

The use of organic fertilisers in very fine turf maintenance is not without drawbacks however. It has been shown that they appear to stimulate the outbreak of turf diseases such as Fusarium patch disease, (caused by the fungus *Microdochium nivale* (Fr.) Samuels & I.C. Hallett) (Lawson 1992 pers. comm.). Also, Goss (1967) and Goss & Gould (1967) suggested that increased occurrence of take-all patch (caused by the fungus *Gaeumannomyces graminis* (Sacc.) V.Arx & Oliver) on *A. capillaris* very fine turf was related to higher soil pH and calcium levels associated with lower rates of application of acidifying fertilisers. These observations would indicate therefore that an acidic, but not "too acidic", substrate is most appropriate for the maintenance of *Agrostis / Festuca* spp. turf.

Slow release fertilisers have been shown to be largely unsuitable for very fine turf in the UK. Escritt & Legg (1968) reported that *A. capillaris* exhibited less growth and poorer colour from mid - July / early August through to the following spring when treated with a single application of sulphur - coated urea than with ammonium sulphate. Urea-formaldehyde showed similar results. Lawson (1992 - pers. comm.) found that slow release fertilisers on very fine *Agrostis / Festuca* turf were generally associated with a much greater ingress of *P. annua* than with conventional, inorganic nitrogen sources.

For very fine *Festuca / Agrostis* turf, recommended rates of nitrogen application range from 140 kg N ha^{-1} yr^{-1} (Escritt & Legg 1969) up to 500 kg N ha^{-1} yr^{-1} (Christians *et al.* 1981), with the majority falling between 200 - 300 kg N ha^{-1} yr^{-1} (eg Lawson 1987). These values were generally arrived at after treating established turf with a range of rates of nitrogen and noting the response in terms of generally perceived "quality" or measuring the contribution to total ground cover of the turfgrass species.

Sources of fertiliser phosphate for turf

The continual removal of plant material without adequate phosphate replacement can lead to phosphate depletion on light soils. Under the intense mowing regimes of golf greens, coupled with high nitrogen inputs, such removal of phosphate from the plant : soil system must clearly take place. It is therefore logical that phosphates must be returned to golf greens if deficiency symptoms are to be avoided.

The most commonly used phosphate fertiliser for golf greens is single superphosphate (18 - 20% P_2O_5, 8 - 9% P). This compound contains 30 - 35% monocalcium phosphate and 65 - 70% gypsum, and consequently also supplies calcium and sulphur to the soil. Phosphates may be applied individually or as N : P : K compounds. The effectiveness of phosphate fertilisation depends however on the soil type to which it is applied. This is discussed below. Application rates are commonly of the order of between 0 and 60 kg P_2O_5 ha^{-1} yr^{-1}.

Potassium fertiliser

The most widely used form of potassium fertiliser is potassium chloride. Shearman (1985) showed that potassium fertiliser application increased wear and drought tolerance and root growth on *A. stolonifera.* Hawes (1984) suggested applying as much or greater amounts of potassium than nitrogen to improve these features on golf greens.

The impact of potassium fertiliser on the botanical composition of mixed species golf greens would appear however to be rather small. In an experiment examining the fertiliser requirements of *Festuca / Agrostis* sand golf greens under UK climatic conditions, (Colclough & Canaway 1989), when potassium fertiliser was applied at three different rates (0, 150 and 300 kg K ha^{-1} yr^{-1}) the highest rate was found to only slightly increase the cover of *Festuca rubra* on plots treated with lime with respect to the other two. Lodge *et al.* (1990), continuing the work, found that potassium's only effect was to reduce the contribution to the ground cover of one species of moss from 7% to 3% in plots treated with lime and the lowest rate of nitrogen.

The dynamics of potassium in the soil are greatly affected by the clay mineral content. Rootzone texture therefore has a profound influence on its availability to the turf. Waddington *et al.* (1972) found that the level of necessary potassium addition to turf depended on the amount of the element naturally present in the soil and on the levels accumulated from applications during the preceding years. Potassium has been shown to be lost from the golf green system in clippings (Markland & Roberts 1969, Skirde 1974) and through drainage (Sheard *et al.* 1987).

Although potassium is recognised as an essential plant nutrient, and research suggests that deficiencies may occur in golf greens (Christians *et al* 1979, Markland & Roberts 1969, Skirde 1974), an examination of the use of potassium fertiliser was not specifically incorporated into the present study, simply because, if it were, the subject area would have expanded too greatly.

1.7 EDAPHIC FACTORS AFFECTING NUTRIENT AVAILABILITY

In addition to their effects on the water relations of the golf green rootzone, soil structure and texture also affect the content and availability of plant nutrients. However, most nutritional studies of turf have been carried out without direct comparison between rootzones of differing texture or structure. This is presumably because distinguishing between the physical effects on the turf of differing soil structure / texture from the effects of the actual movement and availability of nutrients is very difficult.

Factors affecting nitrogen availability

The inorganic fertilisers discussed above supply nitrogen to turf in the form of nitrate (NO_3^-) and ammonium (NH_4^+). Turfgrasses absorb nitrogen as either or both of these ions. Eggens & Wright (1984) found that *A. palustris* cultivars grew better with high NO_3^- in a nutrient solution applied to the plants grown in pot culture in silica sand. *P. annua* grew better with high NH_4^+ concentrations. This would imply that the relative performance of turfgrasses in mixed species communities may be influenced by the soil conditions which affect the abundance and availability of these two ions and by the source of applied nitrogen. The mineralisation of organic matter to NH_4^+ and the nitrification of NH_4^+ to form NO_3^- are influenced by several edaphic factors. Low soil water content limits the mineralisation of organic matter, and the availability of oxygen is crucial to the microbial oxidation of NH_4^+. The structure, texture and irrigation of a golf green may thus affect nitrogen availability to the turf by influencing these processes.

The free-draining nature of some golf greens may facilitate the loss of applied nitrogen by leaching. This subject has been reviewed by Petrovic (1990). Findings indicate that nitrogen leaching losses occur primarily as nitrates (NO_3^-), are higher for soluble inorganic fertilisers and are greater on well - drained, sandy soils (Volk & Bell 1945, Bates & Tisdale 1957, Smika *et al.* 1977, Mitchell *et al.* 1978, Petrovic *et al* 1986). Such losses may not however be very great. Mancino & Troll (1990) found that less than 0.5% of applied nitrogen was lost in leachates collected over ten weeks from *A. palustris* turf grown on an 80 : 20 sand : peat mix. Irrigation was applied at an equivalent rate of 38 mm week^{-1} and nitrogen was applied in 5 and 10 regular applications as differing forms of inorganic fertiliser at rates comparable to those applied to golf greens. Their conclusions were that leachate losses of nitrogen from sand - based golf greens are largely negligible if the total annual nitrogen is applied in small, intermittent doses.

Lawson & Colclough (1991) found that when excessive quantities of ammonium sulphate were applied to *Agrostis / Festuca* spp. turf throughout a UK growing season, leachate losses of nitrogen remained low until the autumn when a high nitrate concentration coincided with a large leachate volume. The largest losses of nitrogen at this time occurred on a sandy loam topsoil, as opposed to mixes of sand and soil. They suggested that much of this nitrogen was derived from microbial mineralisation of fertiliser nitrogen that had been immobilised in roots and soil organic matter during the growing season.

Clay minerals and organic matter enhance the capacity of the soil to buffer pH changes which may take place, notably due to the use of acidifying fertilisers. Soil pH affects microbial NH_4^+ oxidation (Munk 1958), and below pH 5.5 nitrification is limited (Weber & Gainey 1962). Soil pH also affects the relative uptake of NO_3^- and NH_4^+ ions by plants (Rao & Rains 1976). Thus, because soil moisture content and the capacity of the soil to buffer pH changes are greatly determined by physical aspects of the golf green rootzone, the dynamics of nitrogen nutrition must clearly be examined within the context of the water status and the structural and textural nature of the rootzone medium.

Factors affecting phosphate availability

Phosphates are adsorbed onto mineral surfaces in the soil. The rate and extent of adsorption is dependent on the nature and specific surface area of the minerals concerned. This is known as the phosphate buffering capacity (Wild 1988b) and is affected by pH. For most mineral soils, a pH range of between 6 and 7 is optimum for phosphates to remain in solution at their highest concentration. Adsorption is greater at pH 3 - 5, and increases with time, temperature and the phosphate concentration of the soil solution (Barrow 1978). The buffering capacity differs widely for different soils. Webber & Mattingley (1970) found with UK soils that buffer capacity increased with clay content and the amount of extractable phosphate.

Phosphate may be incorporated into the organic fraction of the soil by root production and leaf decay. Soil microorganisms may also directly synthesise organic compounds from inorganic phosphate in the soil solution. The mineralisation of organic matter, by microbial breakdown, consequently provides another source of plant-available phosphate. The amounts of organically held phosphate are therefore related to the organic matter content of the soil, although the phosphate content of organic matter is known to be variable (White & Becket 1964). Because the mineralisation of organic matter is dependent on the degree of microbial activity, factors such as soil pH, aeration and water content presumably affect phosphate release from organic matter in a similar manner to their effects on the release of NH_4^+ and NO_3^- ions.

Phosphate availability is therefore controlled to a large extent by the soil phosphate buffer capacity, the organic matter content, soil pH, and the concentration of phosphate in the soil solution. These relationships are illustrated by Olsen & Watenabe (1970), who found that if continual uptake of phosphate by a growing plant is to take place, clay soils may require a higher rate of phosphate application, and appear to be more deficient than sands or silty soils, because they are more strongly buffered. Similarly, they do not need as high a concentration of phosphate in solution as sandy soils. This has particular relevance when considering the phosphate requirements of golf greens with markedly different rootzone textures.

Soil texture and structure may therefore affect markedly the efficacy of nutrient applications to golf greens. The water - holding capacity of the rootzone affects the activities of nutrients in the soil solution and their rates of loss through leaching. The degree of soil aeration affects the activities of soil micro-organisms and their capacity to release nutrients into the soil solution. The abundance of clay minerals has a direct effect on the cation exchange and buffering capacity of the soil. The presence of organic matter also affects the cation exchange capacity and the potential for nitrogen release by ammonification and nitrification.

1.8 TURFGRASS RESPONSES TO NUTRITIONAL FACTORS

Having considered the mechanisms by which structural, textural and water relations factors may influence the physico-chemical nature of the green and the growth of turf grass, research work examining nutritional effects may now be considered. The nutritional requirements of turf have been greatly studied, and reviews of the subject are provided by Adams (1981), Isaac & Canaway (1987) and Turner & Hummel (1992). Much research has been aimed at identifying the rates of nitrogen fertiliser application necessary for the production of the best "quality" surface. The biological processes occurring within the turf have been less frequently examined directly, but some features do emerge.

Turfgrass responses

It has been recognised for some time that *Agrostis* and *Festuca* spp. grow best in acidic media (Murray 1936, Bradshaw 1962). This observation led to the "Soil Acid Theory" of turf management (Hartwell & Damon 1917, Oakley 1925, Dawson & Greig 1933). The acidifying effects of soluble, inorganic nitrogen sources have been used to obtain the low pH environment deemed appropriate for *Festuca / Agrostis* spp. turf. An experiment designed to examine the use of lime to counteract the acidity induced by the continual application of ammonium sulphate to *Agrostis / Festuca* golf green turf grown on pure sand was described in a series of articles by Canaway *et al.* (1987), and others (Colclough & Canaway 1988, Colclough & Canaway 1989, Colclough 1989, Colclough & Lawson 1989, Lodge *et al.* 1990, Lodge & Lawson 1990). These workers found that lime increased the rootzone pH and prevented the death of *Festuca / Agrostis* spp. due to over - acidification. Ingress of *P. annua* was however enhanced to such an extent by liming that the sown species were largely replaced by the turfgrass weed.

The silt loam and loamy sand soils used in the study referred to above, (Juska & Hanson 1969) which examined the nutritional requirements of *P. annua* grown in pots, were adjusted to pH values of 4.5 and 6.5 by the addition of lime, and two levels of each of nitrogen, phosphorus and potassium fertiliser were applied. On the loamy sand, both top and root growth and seedhead productivity were enhanced at the higher pH, whereas on the silt loam, no significant effects of soil reaction on growth were found. Nitrogen, phosphorus and potassium fertiliser were found to contribute to top growth by degrees decreasing in that order, potassium increasing top growth only slightly. Plants grown on the loamy sand and treated with nitrogen fertiliser, with or without phosphorus and potassium, showed a fall in root : shoot ratio from values around 0.50 to values around 0.10. By contrast, on the silt loam, root : shoot ratios were around 0.12 and were unaffected by the addition of nitrogen. This would imply that the responses of *P. annua* to soil textural/structural phenomena occur in response to nutrient availability which is governed to a great extent by soil type and particularly by soil reaction.

The type of environment in which *Festuca* and *Agrostis* spp naturally occur are generally very similar with respect to soil type and fertility (Grime *et al.* 1988). Where *Festuca* spp. and *Agrostis* spp. are grown in mixed swards maintained as very fine turf, it has been noted by several workers (eg Skirde 1974, Woolhouse 1981, Canaway *et al.* 1987, Lawson 1987) that the percentage cover of *Festuca* spp. generally declines, and *Agrostis* spp. increases with increasing fertiliser input. This response has also been noted in natural hill pastures (Milton 1940) and in pots under greenhouse conditions (Engel 1974). Lemaire (1985) found that *A. capillaris* can easily tolerate the low nutrient levels at which *F. rubra* grows best. When *Agrostis* spp. are selectively removed from mixed, fine turf swards by the disease Take - all (*Gaumannomyces graminis*) the space created is frequently filled by *Festuca* spp., *P. annua* and others. This may suggest that, although soil conditions may be capable of supporting all species concerned, the displacement of *Festuca* by *Agrostis* spp. arises as a result of competition between the two species rather than differing habitat preferences. So the decline in *Festuca* spp. with increasing fertility may be due to its inability to compete with more nutrient - demanding species when nutritional resources are less limited.

Lodge & Lawson (1991), summarising data collected by Canaway *et al.* (1987) and others (Colclough & Canaway 1988, Colclough & Canaway 1989, Colclough 1989, Colclough & Lawson 1989, Lodge *et al.* 1990), examined *P. annua* cover and rootzone pH changes with time of *Agrostis / Festuca* turf grown on pure sand. Plots treated with lime showed a sharp increase over one year in pH (from below 4.5 to above 5.5) after two years of treatment and this coincided with a similarly rapid increase (from 0% to over 30%) in *P. annua* cover. The authors suggested that the pH changes affected nutritional factors which influenced competitive processes occurring between the golf green species, higher pH tending to favour *P. annua* growth.

The enhancing effect of phosphate fertiliser on growth has been much reported (Goss *et al.* 1975, Waddington *et al.* 1978). Lodge & Lawson (1990) reported an increase in *P. annua* cover on sand construction greens in response to phosphate fertiliser rates of 25 and 50 kg P ha^{-1} yr^{-1}, although this effect was only apparent on plots with a high pH due to liming. Juska & Hanson (1969) found that phosphate increased *P. annua* top growth on the loamy sand at low pH, but slightly reduced root growth overall. Root growth response to phosphorus was found to be similar, but less pronounced, than that to nitrogen.

If fertile soils of heavier texture cause *P. annua* root growth to be limited, but produce increased shoot growth, the reported susceptibility of the species to drought under these circumstances (Beard 1970, Beard *et al.* 1978, Peel 1982) may be explained. If the upper layers of the soil profile dry out, *P. annua*, with root growth restricted to this area, is bound to suffer from the unavailability of water, while more deeply rooted species may survive. Youngner (1959) reported that frequent, light irrigation maintained high surface moisture levels in bermudagrass (*Cynodon dactylon*) turf which favoured the persistence of *P. annua.* Koch (1968) found that *P. annua* germination took place when soil moisture lay between 40 and 90% of field capacity, and declined only gradually below 40%. Greater *P. annua* cover on heavier soils, on which the soil surface remains moist for longer, may therefore be due, in part, to its ability to germinate from its prolifically produced seeds.

The effects of fertility and irrigation frequency on *A. capillaris* turf were studied by Madison (1962). On a silty loam soil, increasing rate of nitrogen fertiliser application resulted in greater shoot density, yield, chlorophyll content and "verdure". Verdure was defined as the living grass above the ground not removed by mowing. Individual plant size (verdure divided by the shoot density) showed a slight decline, and total root weight and root weight per plant declined. More frequent irrigation resulted in an increase in shoot density and yield, and decreases in plant size and root weights per plant. Higher fertility and frequent irrigation therefore had similar effects on the turf. Mantell (1966), working with the warm-season grass Kikuyugrass (*Pennisetum clandestinum* Hochst.), found that infrequent irrigation of fertilised turf only slightly reduced quality compared with that obtained when frequent irrigations were given in the absence of nitrogen. It was argued that less frequent irrigation, accompanied by fertiliser applications, conserved both water and labour and was therefore a more efficient management practice. The swards studied by Madison (1962) and Mantell (1966) were grown as pure stands. No similar studies have been carried out on fine turf, mixed species swards.

Canaway (1985 a, b) in the study mentioned above, applied different rates of nitrogen to *L. perenne* turf on sand and soil - based construction types and found that the percentage water content of the shoots increased with increasing nitrogen input. It was suggested that the increasingly succulent plants were less tolerant of wear than those provided with less nitrogen and consequently of lesser moisture content. Tiller number per square metre increased continually with increasing nitrogen application. Above - ground biomass levelled off at nitrogen rates above 400 kg N ha^{-1}. This implied that the mean dry weight per tiller actually declined at higher rates of nitrogen, presumably a response to crowding. In theory, it should therefore be possible to identify the rate of nitrogen input necessary to produce the maximum tiller dry weight, and optimum tiller density, and this may provide the maximum tolerance of wear. In both pasture and cereal grasses, tiller production is known to be greatly increased by raising the supply of nitrogen, phosphorus and potassium (Langer 1966). If, as seems likely, fine turf species behave in a similar fashion, studies which consider the response of individual tillers or plants to differing "habitat" regimes may indicate the most effective management procedures for golf greens, and provide an insight into the mechanisms of interactions between turfgrass species in mixed swards.

1.9 GOLF GREEN "QUALITY"

The effects of treatments on very fine turf have been assessed by many workers by scoring for "quality" (eg Lindgren *et al.* 1988, O'Neil & Carrow 1982, Ledeboer & Skogley 1973, Christians *et al.* 1979). This almost invariably refers to the visual merit of the turf from an aesthetic point of view. A good deal of such research has been targetted at the improvement of fine lawn turf which has no major function other than to be pleasant to look at. However, the quality of a golf green is also determined by the manner in which golf balls respond to the surface during play. Assessment of the quality of golf greens may therefore be divided into two areas, one pertaining to the aesthetic quality, or visual merit, and the other to the playing quality.

A temporal element of both these factors must also be considered. The rising popularity of the game of golf has meant that players expect facilities throughout the UK to be maintained every day of the year. Since turf growth is profoundly affected by the changing seasons, specific aspects of quality may be expected to vary in a similar manner.

Visual merit

The Royal and Ancient Golf Club of St Andrews Greenkeeping Panel stated that "..... as an ideal surface on which to play year-round golf, fescue/bent turf cannot be surpassed" (Anon. 1989b). This would imply that species composition is of importance with regard to visual merit. This aspect of visual merit may presumably therefore be evaluated by quantifying the relative contribution of different species to ground cover. The basic assumption here is that total live ground cover should be maximised and composed of fescue and bent alone, and the abundance of *P. annua,* along with other weed species, which are generally considered undesirable, should be nil. No studies have been carried out to establish directly what sward composition golfers, the "consumers", actually prefer.

The simplest means of obtaining an impression of what is meant by turf visual quality is to ask people to score turf according to their own subjective opinion. This is basically a form of market research. Subjective scoring of turfgrass visual quality was investigated by Horst *et al* (1984) working with different cultivars of Kentucky bluegrass (*Poa pratensis* L.) and tall fescue (*Festuca arundinacea* Schreb.). The relative rank performance of cultivars was found to differ between evaluators. These workers concluded that the results of trials assessed in this manner should be treated with caution because individual evaluators either did not use the same criteria for evaluation or were not consistent with their visual assessment.

Some research has been directed towards finding objective techniques of assessing turfgrass visual merit so that the limitations of subjective evaluation may be avoided. The ability of chlorophyll to absorb red (R) and reflect near infra-red (NI) light wavelengths has been exploited by workers to develop techniques of turf evaluation. Birth and McVey (1968) found that the ratio of NI to R, measured by a reflectance spectrophotometer, of different grass species receiving different levels of nitrogen fertiliser correlated with visual colour score, and Biran & Bushkin-Harav (1981) utilised a light meter capable of measuring the reflectance of NI/R to describe the intensity of colour between 10 different turfgrass species. Gooding and Gamble (1990) showed that reflectance ratio could be used to provide a method of assessing the combined effects of turf cover and colour of turf cultivars. These workers used a reflectance ratio meter (Haggar & Isaac 1985) which gave the NI (peak at 750 nm) to R (peak at 650 nm) ratio.

More specific examination of turfgrass colour has been carried out using colour meters which give quantitative descriptions of colour using "L" (white - black), "a" (red - green) and "b" (yellow - blue). Kavanagh *et al..* (1985) used such a device to describe the colour of different turfgrass species and the effects of iron sulphate application. Kimura *et al..* (1989) described the colour of different cultivars of *Agrostis* spp, *Poa pratensis* L., Festuca spp. and *Lolium perenne* L. in the field.

Colour and reflectance assessment of mixed species swards is difficult to interpret biologically. Such readings may be said to represent the net effect of three components: the overall cover of live material, the intrinsic chlorophyll density, or colour, of the species present, and the relative contribution of each species to the whole sward. The monitoring of colour and reflectance ratio of mixed species swards is therefore of limited value because different readings may arise due to any one or all three of these components, each of which is of quite distinct biological significance.

The relationship between visual merit and the morphology of individual plants and of the sward as a whole has also been investigated. Gooding and Newell (1991) found a relationship between shoot density and visual merit in *Poa pratensis* L. cultivars and Gooding and Newell (1990) concluded that shoot density could provide a simple, objective method of assessing turfgrass performance of *Festuca* spp. cultivars. Fine leaf widths have also been associated with visual merit. As shoot density increases, leaf width was shown to become finer (Turgeon 1985) and Brede and Duich (1982) reported that increasing sowing density decreased leaf widths in *Poa pratensis* cultivars.

The pattern of distribution of species almost certainly influences visual merit scoring and is a feature which is independent of individual species cover. The weed species *Poa annua* L., for example, tends to grow in a dense, spreading pattern, and this is generally considered unsightly. Also diseases such as take-all patch cause distinct circular patches of dead *Agrostis* spp. surrounding a legacy of *Festuca* spp. or weed species. This therefore affects the pattern of species distribution in mixed species swards. Several methods of analysis of pattern have been devised and are discussed by Greig-Smith (1983). No such studies have been carried out on fine turf.

Playing quality

In terms of the game of golf, a green has two functions with respect to the ball in play. These are the provision of a suitable playing surface over which the ball is rolled during putting and of a landing area for downcoming balls. The manner in which the green affects the nature of these two processes contribute to the overall concept of the green's quality. Intuitively, the set of characteristics of greens which chiefly affect ball behaviour in these two situations differ.

The interface between a ball rolling over a green surface after a putting stroke will be affected by some or all of the following factors: [i] the species present in the turf and their relative abundance; [ii] the pattern of species distribution; [iii] the height of cut; [iv] the relative growth rate of each species (since growth will take place after mowing); [v] the form of growth of individuals within species; [vi] the degree of surface moisture retention; [vii] the turgor or pressure potential of the grasses; [viii] the "overall" hardness of the turf at the level of interaction brought about by the rolling ball. Depth of thatch may be influential in this last respect. Moreover, interactions between these factors will take place. For example, surface moisture retention on *Agrostis* spp. is greater than on *Festuca* spp., a phenomenon which may be observed in the distribution of dew on greens in which these two species occur in patchy distribution.

All the above factors may conceivably affect the behaviour of iron shots following impact with the green surface. The nature of the impact will also vary in relation to the spin, velocity and angle depending on the choice of club and the manner in which the ball is hit. However, a large number of additional factors will influence the nature of the impact since the vertical movement of the ball creates interactions with deeper layers of the turf profile. Subsequent ball behaviour will therefore be influenced by the characteristics of any thatch layer present, the physical nature and moisture content of the rootzone medium and the form and extent of rooting within this.

How features of golf greens affect ball roll has received some research interest. A device, known as a Stimpmeter (Stimpson 1974, Radko 1977a,b, 1978), designed to produce a "standard" putt has formed the basic tool of this work. Radko (1977a) developed a set of green speed standards for the Stimpmeter, classifying a range of speeds appropriate for regular membership and tournament play. Colclough (1989) found that increasing the rate of nitrogen fertiliser applied to fine turf grown on pure sand decreased speed. On plots treated with lime, green speed was less than on un-treated plots, and phosphate fertiliser decreased speed on limed plots. Engel *et al.*. (1980) found an approximately 25 % reduction in green speed when mowing height was increased from 4.69 mm to 6.25 mm and found between 8 and 10% variation in speed depending on the "nap" of the turf brought about by the mower.

Research into the more complex field of golf ball impacts with natural turf is much less extensive. The management of golf green turf with respect to its ability to "hold" balls was discussed by Buchanan (1984). Research has been limited by the difficulty in simulating the trajectory and spin characteristics of iron shots. Haake (1991a) however developed an apparatus able to project golf balls downward with a known angle of impact, degree of backspin and velocity. Colclough (1989), using this device, was the first to attempt to describe the effects of turf management factors on the outcome of golf ball impacts onto fine turf. He measured the distance between the initial impact and the final resting place of the ball. This distance he related to the "holding power" of the turf since it reflected the ability of the turf to retain the backspin imparted onto the ball after being struck by a club. Small stopping distance values were considered to be desirable. On a pure sand construction, he found that stopping distances decreased as nitrogen input was increased from 100 to 400 kg N ha^{-1} yr^{-1} and was greater on plots not treated with lime.

The apparatus required to simulate golf ball impacts is cumbersome and the data difficult to obtain. If ball impact behaviour could be related to some other turf characteristic which was more readily measured, the playing quality of greens could be more easily assessed. To this end Colclough (1989) measured the hardness of the turf using a Clegg Impact Soil Tester (Clegg 1976). This device measures hardness as the rate of deceleration experienced by a falling weight on impact with the surface being tested. He found that hardness declined with increasing nitrogen input and, like stopping distance, was greater in un-limed plots. Hardness, measured with this apparatus, is known to have an influence on the impact behaviour of footballs (Baker and Isaac 1987, Bell and Holmes 1988) and cricket balls (Lush 1985).

1.10 RESEARCH OBJECTIVES

Construction, irrigation and fertiliser nutrition represent major areas of golf green management. A sound understanding of the processes involved when these factors are utilised in order to create or improve golf green surfaces can only aid their effectiveness. The general objective of this research was to improve our understanding of how these processes affect *Festuca / Agrostis* golf greens in the UK.

A field trial was prepared which facilitated the examination over several years of golf green surfaces on three different construction types supplied with low, medium or high amounts of irrigation and five rates of nitrogen fertiliser with and without phosphate fertiliser. Each of the 90 combinations of these treatments were studied.

The study was largely empirical. That is, treatments were applied and their effects examined and described. Historically, this approach has been adopted whenever a science is in its early stages of development. In many respects the study of sports turf surfaces in general has suffered from a lack of appreciation given to the basic biological and physico-chemical processes involved. This has most likely come about due to the highly commercially targetted nature of most of the research work carried out. One of the main aims of this study was therefore to highlight the principles involved when considering particular aspects of golf greens and their maintenance, to define the science in effect. Our understanding of turfgrass may therefore be improved by the judicious drawing upon scientific work in seemingly unrelated areas.

The management of golf green turf is aimed at maintaining a quality surface for play throughout the year. Factors contributing to the quality of this surface are its physical nature, pertaining to the structure, texture and water-holding capacity of the rootzone, its visual appearance, pertaining to the extent and form of species cover, and the combined effects of these two factors on the behaviour of golf balls in play. By examining the influence of management factors on each of these three components of "quality", it was envisaged that the biological and physico-chemical processes involved may be described and better understood.

The three different forms of golf green construction were therefore described in the more applicable terms of soil texture, structure and profile. Since these features are known to affect greatly the behaviour of water in soil-plant-atmosphere systems, soil water retention, drainage and ET were also studied. The visual quality of the turf was examined primarily in terms of the effects of the treatments on the botanical composition of the swards. This was carried out alongside studies of the nutrient content of the soil. The objective here was to generate hypotheses concerning the ecological processes relating these features, soil-water relations and the observed sward characteristics.

The playing quality aspects of turf quality were approached with the view that golf ball behaviour is determined chiefly by the player and the surface. The influence of the surface takes place through many of the physical and biological characteristics described above. It was envisaged therefore, that relationships between the effects of treatment factors on turf characteristics and golf ball behaviour (under controlled circumstances) could be identified.

Since the interactions between management factors and turfgrass responses are very complicated, straightforward indications of appropriate management practices in given golfing situations are difficult to provide. The relative effectiveness of different practices in bringing about improvements are frequently not fully appreciated. The feasibility of using an holistic approach to the relationships between management and quality was therefore explored. This approach was based upon techniques of multivariate analysis used in studies of natural ecological systems. The identification of a set of readily measurable features which together summarised the quality of a golf green surface, was necessary. Using these, the surface could then be classified into one of a set of possible types and management recommendations aimed at its improvement, and specific to that type, could then be provided.

CHAPTER 2 - EXPERIMENTAL DESIGN AND ASSOCIATED STUDIES

2.1 INTRODUCTION

The empirical objectives of the research were to define the most appropriate fertiliser and irrigation regimes required to produce the "best" golf green turf on differing construction media. The treatment factors under investigation represented fundamental tools in the hands of turf managers, but they could not be considered in isolation from one another. Interactions between factors needed to be examined. This necessitated a large field trial involving the controlled application of different irrigation and fertiliser treatments to different construction media. This chapter describes the methodology, establishment and maintenance procedures of this trial.

The present study began in October 1990. Preparatory work for the project began in April 1989. In order to provide a full description, it was therefore necessary to include in this chapter work carried out prior to the onset of this study.

2.2 STATISTICAL DESIGN, ANALYSIS AND PRESENTATION

When designing the field trial, a randomised block design was decided upon. This permitted a degree of control of local variation due to environmental factors such as slope and the effects of cut and fill during levelling work. The imposition of irrigation treatments meant that, if installation and running costs were to be kept reasonable, a fully randomised plot design was impossible. In the case of overhead irrigation, it is more practical to irrigate at the same rate a large plot divided into smaller sub-plots, rather than irrigate each sub-plot individually. Similarly, it is more economical to install and maintain fewer areas of the same construction and sub-divide these, rather than individually construct each experimental treatment unit. The design was therefore refined so that main plots, for irrigation treatments, were divided into sub plots of differing construction. Fertiliser treatments could then be applied to sub-sub-plots, within the construction sub-plots, in a split-plot, randomised-block experimental design.

The experimental treatments consisted of three levels of irrigation (1, 2 &3), three types of golf green construction (sand, USGA and soil), five levels of nitrogen fertiliser (N1 to N5) and two of phosphate (P1 and P2). The trial was divided into two blocks. The three irrigation treatments formed the main plots in each block. Each main plot was 12 m x 12 m and separated from each other by 2.5 m wide pathways. Each main plot was split into three 12 m x 4 m sub-plots, to each of which was randomly assigned the construction types. The construction sub-plots were further sub-divided into twelve 2 m x 2 m sub-

sub-plots, two of which in each sub-plot were set aside for the reasons described below. The five nitrogen and two phosphate fertiliser treatments were factorially arranged and randomly allocated to the ten remaining sub-sub-plots in each sub-plot. The end result of the design and three randomisation procedures is illustrated in Figure 2.1.

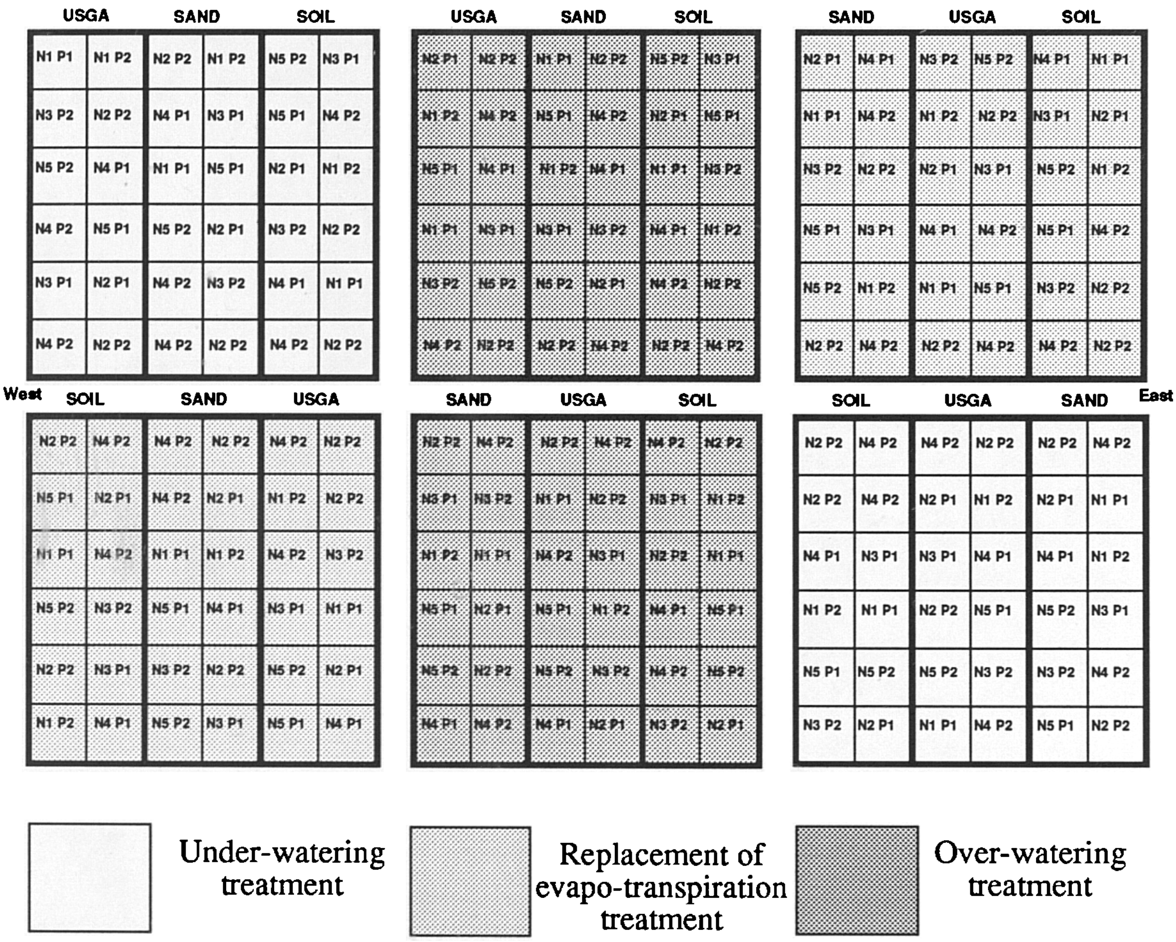

FIGURE 2.1
The trial randomisation. N = nitrogen, P = phosphate.
The construction types are indicated above each sub-plot. The irrigation treatments are indicated by the intensity of shading.

The basic experimental treatment area (2 m x 2 m) of the sub-sub-plots provided sufficient space to carry out visual assessments, ball behaviour and other physical tests, and showed a suitably homogeneous response to fertiliser application while keeping edge effects to a relative minimum.

The 36 remaining sub-sub-plots were set aside to provide irrigation, construction and nitrogen fertiliser-treated sub-sub-plots for carrying out destructive sampling procedures.

These were all located adjacent to the footpath separating the two blocks for ease of access, and were allocated the P2 phosphate treatment. Nitrogen treatments were applied at the N2 and N4 rates, representing low and high inputs, and were randomly assigned to each of the two destructive sampling sub-sub-plots (DSPs) in each construction sub-plot.

The choice of five rates on nitrogen fertiliser was made to facilitate the recognition of curvature in nitrogen response data. Statistical tests of curvature were incorporated into analysis of variance (ANOVA) procedure using linear, quadratic and cubic polynomial fitted curves. By choosing five levels, the option of fitting more specific models, for example those derived from asymptotic regression or inverse polynomial relationships which have been frequently used to model plant responses to nitrogen application (eg Canaway 1985a,b) was maintained. The actual rates of nitrogen applied, and the form and quantity of phosphate fertiliser used, are discussed in Section 2.9.

IRRIGATION	2
RESIDUAL	2
CONSTRUCTION	2
IRRIGATION x CONSTRUCTION	4
RESIDUAL	6
NITROGEN	4
PHOSPHATE	1
IRRIGATION x NITROGEN	8
CONSTRUCTION x NITROGEN	8
IRRIGATION x PHOSPHATE	2
CONSTRUCTION x PHOSPHATE	2
NITROGEN x PHOSPHATE	4
IRRIGATION x CONSTRUCTION x NITROGEN	16
IRRIGATION x CONSTRUCTION x PHOSPHATE	4
IRRIGATION x NITROGEN x PHOSPHATE	8
CONSTRUCTION x NITROGEN x PHOSPHATE	8
IRRIGATION x CONSTRUCTION x NITROGEN x PHOSPHATE	16
RESIDUAL	81

TABLE 2.1

Skeleton ANOVA table for the treatment structure showing degrees of freedom within each stratum.

A skeleton ANOVA table, not incorporating tests of curvature of nitrogen response, but giving degrees of freedom for each level in the ANOVA structure, is shown in Table 2.1. The irrigation and construction/irrigation strata of the ANOVA table have their own residual mean squares which were used to generate "F" ratios and standard errors of differences between appropriate means. This is normal procedure for analysing split-plot experiments. For certain aspects of the study, sequential observations of the same variables were made on each of the sub-sub-plots over the trial period. When comparisons of the means of such observations were to be made between assessment dates, a single split-plot analysis of all the relevant data was performed, regarding time as an additional split-plot treatment. An additional stratum of time was therefore incorporated into the ANOVA table, above the irrigation stratum (Table 2.1).

Pearce (1953) suggested that the split-plot approach was appropriate for the analysis of repeated observations on perennial crops, and this view was supported by Steel & Torrie (1960) and many workers have subsequently adopted this method of analysis (eg Thomas & Wilkinson 1975, Barry 1976). Rowell & Walters (1976) pointed out that with such an analysis, the split-plot classification (time) is not randomised as it should be for a genuine split-plot design. These authors suggested that a more appropriate analysis would consist of the analysis of contrasts of linear functions of the variables over time. The interpretation of such an analysis of the data obtained in this study is however extremely difficult and demonstrates a degree of complexity which, when described in full, tended to obscure the basic goals of the project. For this reason, the split-plot approach described above was employed where necessary.

A major difficulty encountered with experiments consisting of several main effects and many interactions is one of the presentation of means which may be significantly different from one another in interactions between treatments of several orders. The limitations are brought about by the two-dimensional page on which the data are presented, and also in the visualisation of such interactive effects in the mind of the reader. It was therefore necessary, on occasions, to present the means of lower orders of interactions when those means were themselves the product of significant but higher interactive effects. In general, if a significant interaction F - ratio was small in comparison with that of the main effect, then the main effect means were considered in addition to those of the interaction. If the interactive F - ratios were greater than those of the main effects, only the interactive means were considered.

2.3 SITE PREPARATION

The location of the experimental ground was the Sports Turf Research Institute, Bingley, West Yorkshire, England, N.G.R. SE 095391. The trial was sited on a slight slope with a southerly aspect at an elevation of 211 m above mean sea level. Construction work on the trial was completed by August 1988, when seeding of the area took place.

A plan view of the main construction features of the trial is shown in Figure 2.2. The original slope of the ground was from the top of the plan (northern edge) to the bottom (southern edge).

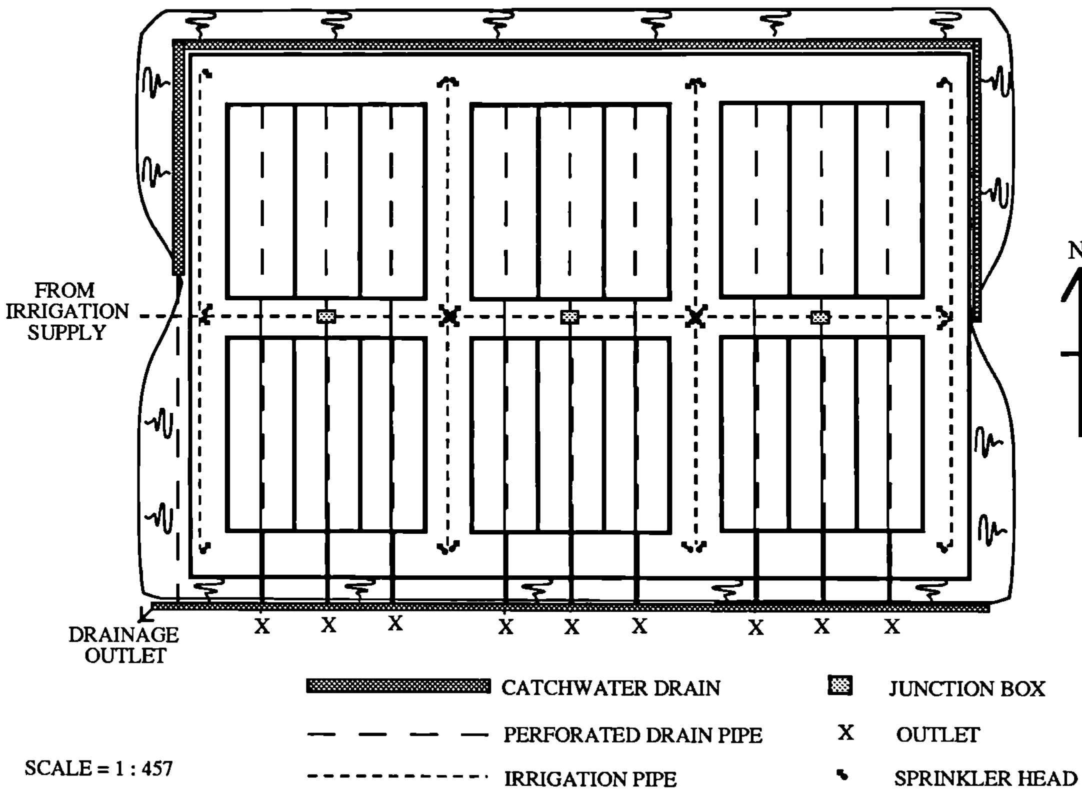

FIGURE 2.2
Plan view of the main construction features of the trial.

The initial construction work involved:-

i) The levelling of the trial area by the cut and fill principle.
ii) The introduction of catchwater/intercept drains.
iii) The introduction of sub-plot pipe drains.
iv) The introduction of pipework and electrical control system for the irrigation system.

i) Site levelling

Having removed the top 350 mm of topsoil from the affected area of the initial slope, and excavated other waste material to the surface of the sub-soil, levels were adjusted over the designated area to produce a smooth surface with a regular gradient of 1 in 80 from the north to the south.

ii) Catchwater / intercept drainage

Catchwater drains were installed to prevent surface and sub-surface run-off water, from areas around the trial of higher elevation, flowing onto the trial itself and the area immediately to the south. Drains were laid with a fall of not less than 1 in 100 toward the outlet. Perforated plastic drainpipes (to BS 4962:1973, diameter 110 mm) were set in trenches of minimum depth 600 mm to invert, and width 150 mm. The trenches were back-filled, to a depth of 75 mm from finished ground level, with the lightweight aggregate, "Lytag". This material, discussed later in the chapter, is a synthetic form of pea gravel. The drains were capped off with 75 mm firmed depth coarse sand.

iii) Pipe drainage of sub-plots

Each sub-plot was independently drained by means of a single perforated plastic pipe (to BS 4962:1973, diameter 80 mm) set into the levelled subsoil. The precise mode of installation of the pipe drains varied with the construction treatment of the sub-plot and is discussed in the following section. At the southern end of each sub-plot the perforated pipe was connected to un-perforated plastic pipe (to BS 4660:1973, type 1420). This pipe continued through the sub-soil to emerge from the southern banking. End stops were installed to seal the northern open ends. By this means drainage water from each sub-plot could be independently collected, or fed into the southern-most catchwater. This arrangement is shown in Figure 2.2.

iv) Irrigation system

Trenches were excavated to a depth of 350 mm to invert below the subsoil formation surface to house the sprinkler supply pipes and control leads. Glass-fibre reinforced cement junction boxes were installed to house control features of the irrigation system.

2.4 THE CONSTRUCTION TREATMENTS

Installation of construction treatments

Each sub-plot was excavated to the appropriate depth in the sub-soil, and drain trenches were installed and the pipes set into them. All four sides of each plot were lined, before the incorporation of drainage and rootzone material, with 300 guage polythene sheeting from the sub-soil level to the finished level of the trial. This was intended to inhibit lateral movement of water and roots between sub-plots and to and from paths, and to avoid mixing of rootzone media.

The three construction treatments incorporated into the trial included two suspended water table (SWT) designs, with either a pure sand or a USGA (United States Golf Association) specification rootzone, and a simple topsoil construction. Transverse cross sections of each construction treatment are shown in Figure 2.3. It should be noted that the sand and USGA cross sections are identical in all but the actual rootzone media used. The USGA specification for the rootzone mixture (USGA 1989) was arrived at by mixing 10% by volume of the local topsoil with 15% by volume sterilised Irish sphagnum moss peat and 75% sand.

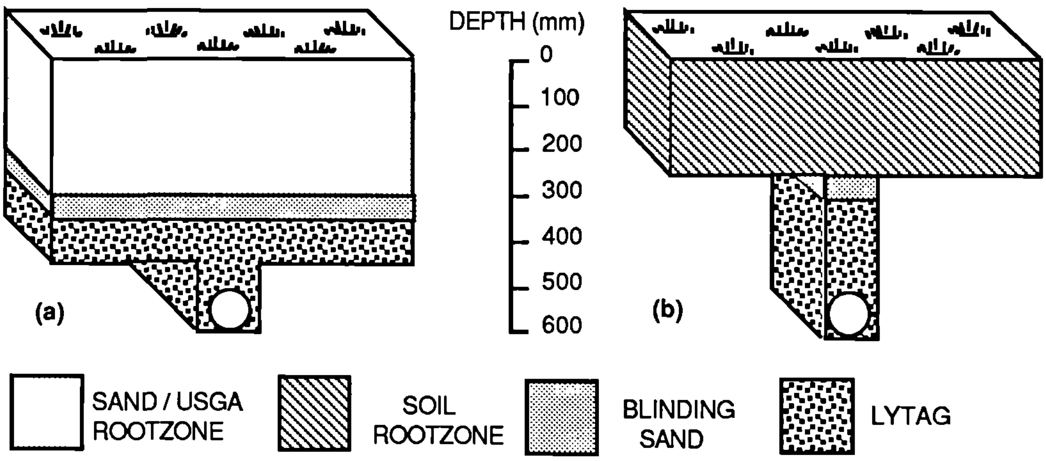

FIGURE 2.3
Schematic cross sections of the construction types.
a) Sand and USGA construction.
b) Soil construction

Particle size characteristics of construction media

An assessment of the particle size distribution and organic matter content of the construction media provides a basic but convenient description of the materials used in the installation of the trial. Such an analysis was carried out on all the construction treatment materials, with the exception of the Lytag, in order to obtain a general impression of the physical nature of the materials used.

Particle size distribution data, or mechanical analysis data, of the media were obtained by the method of Piper (1942). Briefly, prior to sieving, the removal of cementing agents and organic matter was carried out by boiling air-dried samples with hydrogen peroxide until all gaseous hydrogen peroxide had been removed. Samples were then shaken for two hours with 10% sodium hexametaphosphate in order to bring about the deflocculation of soil colloids. Sand fractions were determined by sieving the dried soils through successively finer sieves. Silt and clay fractions were determined by sedimentation.

Soil organic matter was determined by loss on ignition. Weighed, air-dried samples were ignited at 400°C for eight hours and then reweighed. The resultant loss in weight was expressed as a percentage of the weight before ignition. This method is described by Baker (1985). The results of the particle size distribution and organic matter content of the construction media are shown in Table 2.2.

CATEGORY	DIAMETER (mm)	BLINDING SAND	SAND	USGA	SOIL
Stones	>8	1	0	0	3
Coarse gravel	8-4	7	0	0	2
Fine gravel	4-2	15	0	0	3
V. coarse	2-1	12	0	1	5
Coarse sand	1.0-0.5	34	1	22	11
Medium sand	0.50-0.25	24	55	66	15
Fine sand	0.250-0.125	5	41	6	16
V. fine sand	0.125-0.050	1	1	1	14
Silt	0.050-0.002	1	1	2	24
Clay	<0.002	0	1	2	15
Organic matter content (%)		-	0	0.8	4.7

TABLE 2.2

Particle size distribution of the rootzone media and blinding sand (% by weight in each size fraction.)

2.5 SEEDBED PREPARATION AND SOWING

Sterilisation of the soil and USGA sub-plots was necessary in order to eradicate weed seeds and turf pests and diseases such as nematodes, soil-borne fungi and soil insects. The sand sub-plots were assumed to be sterile in this respect. Sterilisation was achieved by treatment with methyl bromide gas.

Following sterilisation, soil sub-plots were cultivated using a hand-operated mechanical cultivator to relieve compaction throughout the full depth of the rootzone. In order to improve the water retention capacity of the sand surface during the vital period of seed germination, the commercial seaweed-based soil improver "Alginure" was raked into the surface of the sand sub-plots at a rate of 75 g m^{-2}. This product contains gelatinous alginates which are able to absorb water, but eventually break down through biological decomposition.

Alternate hand-raking and heeling of the seedbeds was carried out to produce a smooth, evenly firmed, fine tilth for the sowing of seed. Stones and other deleterious materials were raked up and removed from the soil sub-plots during this process. Shortly before seeding was carried out, the seedbed fertiliser "Floranid" (BASF) (N:P:K - 15 : 9 : 15) was evenly applied at a rate of 40 g m^{-2}, and raked into the surface.

The seed mixture used for the main plots was an 80 : 10 : 10 blend, by weight, of *Festuca rubra* ssp. *commutata* cv. Frida : *Agrostis castellana* cv. Highland : *Agrostis capillaris* cv. Bardot. The total quantity of seed required was divided into two, each half being sown evenly, by hand, in transverse directions and then lightly raked in. All seedbeds were sown at a rate of 35 g m^{-2} in week 35 (August) 1988. Throughout the ensuing germination period, the surface of the trial was kept moist by irrigation with the sprinkler system as and when necessary.

2.6 MAINTENANCE DURING TURF ESTABLISHMENT

The imposition of the irrigation and fertiliser treatment programme began 18 months after sowing had taken place. In real golfing circumstances, a green constructed in August would receive play the following spring, only six months after seeding. It was necessary however to extend this period by one year due to poor rates of turf establishment.

The establishment period was considered to be complete by the time of the first treatment fertiliser in week 15 (April) 1990. Prior to this, management procedures were carried out to produce turf able to withstand the close-mowing and wear received by golf greens. These procedures were categorised as follows:-

i) Fertilizer
ii) Mowing
iii) Verti-cutting
iv) Top-dressing and levels adjustment
v) Pesticide applications
vi) Spiking and verti-draining
vii) Irrigation

The maintenance work received by the trial during the eighteen month establishment period is described for each category.

i) Fertilizer

Prior to the winter of 1988/89, a single dressing of ammonium nitrate ("Nitram" - ICI) was applied to the sand sub-plots at a rate of 5 g m^{-2}. This took place in week 43 (October). Throughout the growing season of 1989, fertiliser was applied to the entire trial area. The first two dressings were of an N : P : K fertiliser of the "Longlife" (ICI) series, (14 : 3 : 7). Subsequent dressings were of "Nitram". "Longlife" was applied in solid form by hand.

WEEK NUMBER	RATE (kg ha^{-1})	FORM	METHOD
18 (June)	220	14 : 3 : 7	By hand
22 (June)	220	14 : 3 : 7	By hand
25 (June)	57	"Nitram"	In solution
28 (July)	57	"Nitram"	In solution
31 (August)	60	Iron Sulphate	In solution
35 (August)	57	"Nitram"	In solution
39 (September)	57	"Nitram"	In solution
41 (October)	57	"Nitram"	In solution

(N.B. 57 kg ha^{-1} "Nitram" = 20 kg ha^{-1} N, 220 kg ha^{-1} "14:3:7" = 31 kg ha^{-1} N)

TABLE 2.3
Fertiliser dressings applied to the trial during the 1989 growing season.

"Nitram" was applied in solution using a pedestrian pressurised trolley sprayer with a 2 m boom (Drake and Fletcher). The date, form, rate and method of application of fertiliser during the 1989 growing season are summarised in Table 2.3.

ii) Mowing

The length of time between cuts was largely determined by the perceived growth rate of the turf. Soil sub-plots were first mown 4 weeks, USGA 5 weeks and sand sub-plots 7 weeks after sowing. Throughout the winter, mowing took place once per month, and this was gradually increased so that from April to September it was carried out twice per week. The height of cut was gradually reduced from 25 mm after sowing to 19 mm in week 16 (April) 1989 and further to 13 mm in week 22 (May) 1989. This height was maintained until week 1 (January) 1990 when it was reduced to 10 mm and then to 8 mm in week 13 (March) at the start of the experimental fertiliser treatments. The mowers used throughout this period were pedestrian single-cylinder mowers with ten blades per cylinder.

iii) Verti-cutting

The condition of the turf in 1988 was too delicate to facilitate any verti-cutting. This procedure, which involves passing a series of vertically rotating blades across the turf in order to cut through horizontally-growing leaves and stolons, was first carried out in weeks 29 (July), 37 (September) and 41 (October) 1989 on both soil and USGA sub-plots. The blades were set very lightly so as to just flick the rootzone surface. Verti-cutting was not repeated until the fertiliser and irrigation treatments had begun.

iv) Top-dressing and levels adjustment

Top-dressing is a procedure carried out only on established turf during the growing season. Throughout the establishment period, only the soil sub-plots were treated with one dressing of USGA mix at a rate of 1 kg m^{-2} in week 29 (July) 1989. No other routine maintenance top-dressing was undertaken.

During 1989, settling of the rootzone materials took place producing numerous low-spots on some sub-plots. This occurred most notably on the soil constructions. Low-spots tended to occur at the southern, drain-outlet ends of the sub-plots. A levelling survey was carried out in week 20 (May) 1989 in order to reveal the degree of deviation from the intended plane of the trial surface. Levels were taken at 1 m centres over each plot. A contour diagram of one of the worst affected plots is shown in Figure 2.4. Contour heights, at 10 mm intervals, represent the heights above (positive) or below (negative) the average north - south sloping plane of the plot surface relative to a temporary bench mark (TBM), located 36 m from the trial centre. The development of distinct interfaces between two construction types within the plots is clearly indicated, as is the subsidence on the drain outlet end of the soil sub-plots.

The problems associated with the levels were two-fold. Firstly, sharp changes in ground height may lead to "scalping" of the turf during close mowing. Secondly, the existence of low spots may contribute to loss of uniformity in the amounts of rain and irrigation water reaching the surface of the plots. In the case of the soil constructions this phenomenon was particularly serious since rain and irrigation water were frequently received at rates exceeding the water infiltration rate of the rootzone medium. Lateral water movement would therefore take place and result in ponding in the low-spot areas.

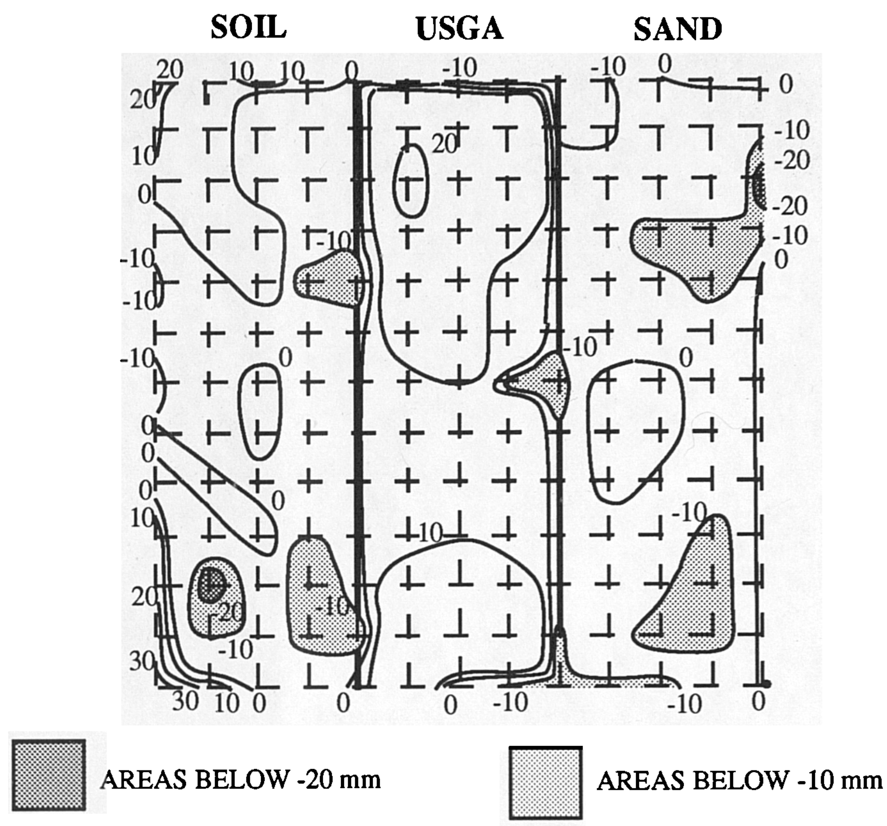

FIGURE 2.4
Contour diagram of the most undulating plot in week 20 (May) 1989, adjusted to remove the overall north - south slope effect.

The correction of levels may be achieved by either or both of two means. Low areas may be raised slowly by the gradual application of top-dressing to the appropriate area. Over several months during the growing season, this method can raise levels by up to about 15 mm. In situations in which areas need to be raised (or lowered) by heights greater than this, cutting and lifting of the of the established turf is necessary.

In four areas on three of the six soil constructions the surface had depressed by more than 25 mm below the general plane of the plot. These areas were raised by the addition of heat-sterilised soil beneath the turf which was lifted using a motorised turf cutter with the blade set at a depth of 35 mm. The operation was carried out in week 29 (July) 1989. After replacement of the turf, the areas were lightly rolled. A further correction of the plot levels was carried out by applying the respective rootzone media as topdressing to each square metre of the plots, the quantities applied depending on the necessary amount of lift. One quarter of the total volume necessary in theory for the lift was applied in this manner in week 29 (July) 1989. Thereafter the levels were considered to be satisfactory.

v) Pesticide applications

During the establishment period, three pesticide applications were made. The first two took place in weeks 38 (September) and 43 (October) 1988, one and two months after seeding. These were both with the fungicide "Brassicol" (Rhone-Poulenc), the first application being made to soil sub-plots, the second to the entire trial. The active chemical in this compound is quintozene and it was used to prevent *Fusarium* spp.-induced seedling diseases such as seed rot and pre - and post-emergence damping off. The third application took place in week 6 (February), 1990 and was of "Gammacol" (ICI), a gamma- HCH-containing formulation designed for the treatment of "leatherjackets" or Crane-fly larvae (*Tipula paludosa* Meig.). These organisms feed on underground grass stems and roots and severe outbreaks may cause serious damage to turf. All pesticide applications were made using the pedestrian pressurised trolley sprayer with a 2 m boom (Drake and Fletcher).

vi) Spiking and verti-draining

No spiking treatments were carried out until week 43 (October) 1989. Using slit tines of 150 mm depth and 180 mm separation, spiking was carried out weekly throughout the remaining weeks of 1989 and fortnightly until the beginning of fertiliser treatments. One pass with the machine was carried out in each case.

To improve drainage on the soil construction sub-plots, a single verti-drain treatment was carried out in week 34 (August) 1989. The verti-drain machine, mounted on a turf tractor, was equipped with 250 mm, solid tines of 12 mm diameter set at 50 mm spacings. The tines swung through an angle of 20° - 25° when thrust into the ground to their full extent. Immediately prior to this treatment, USGA rootzone mix was spread over the soils at a rate of 5 kg m^{-2}. This was worked into the verti-drain holes afterwards.

The effectiveness of the verti-drain was tested by measuring the water infiltration rate of the DSPs before and after treatment. This was achieved using the method of Schmidt (1980). Two steel rings, of depth 200 mm and approximate diameters 300 and 500 mm, were arranged concentrically and hammered into the turf to a depth of about 50 mm. Both rings were then filled with water and maintained in this condition for 15 minutes in order to saturate the ground beneath each prior to rate measurement. Infiltration rate was then recorded by measuring the height fallen by water in the inner ring over a given time. Values were corrected for the variation in the viscosity of water with temperature by adjusting to a common temperature of 10 °C. The purpose of the outer ring was to reduce errors in the measurement caused by the lateral movement of water through the soil. Each of the destructive sampling sub-sub-plots was measured in this way, taking five measurements from each.

The verti-drain treatment had the effect of increasing surface water infiltration rates from a mean value of 2.5 mm hr^{-1} (standard error [SE] = 0.08) to 22.3 mm hr^{-1} (SE = 2.5), measured in weeks 33 (August) and 45 (September) 1989. This was considered to be satisfactory.

vii) Irrigation

The overall daily irrigation requirements were calculated using specialist software (TORO Network 8000 System) on an IBM computer linked to an automatic weather station located 74 m from the centre of the trial. Solar radiation, wind speed and direction, air temperature and humidity were relayed to the computer which calculated the daily evapo-transpiration (ET) using an unspecified and inaccessible derivation of the Penman equation (Penman 1948, 1963) that was not specified by the manufacturers. Precipitation was also measured at the weather station and this was subtracted from the demand ET figure. The sprinkler systems were then activated, one by one, for the required duration to replace the theoretically-derived and precipitation-adjusted moisture loss.

Irrigation of each main plot was initially achieved through four pop-up sprinkler heads, installed during construction (Section 2.3 iv.), and arranged in a rectangle of sides 12.53 m and 13.96 m, the longest side parrallel to the central footpath and orthogonal to the construction types. The sprinkler heads used were TORO XP 300 with an output rate, according to the manufacturer, of 8.49 l min^{-1} when turning through an arc of 90° with a pump pressure of 50 psi. Over the area irrigated by each set of four pop-ups, this produced a theoretical irrigation rate of 11.6 mm hr^{-1}. In week 49 (December) 1989 these heads were replaced by the larger TORO 640 (nozzle size 40) heads and the pump pressure was adjusted to 100 psi. These heads were arranged in a square around each plot of side 14.85 m. This allowed 1.43 m to reduce edge effects brought about by wind drift during sprinkler operation.

During the establishment period the XP 300 system was employed to provide daily replacement of ET from the sowing period (week 34 [August] 1988) until week 42 (October) 1988, and from week 15 (April) 1989 until week 42 (October) 1989. From week 10 (April) 1990 until week 15 (April) 1990, when differential irrigation treatments began, the TORO 640 system was employed in the same manner. Irrigations took place daily at 24:00 hours, unless frost threatened in which case they were carried out at 17:00 hours. Throughout the summer of 1989 the system was manually activated for periods of between 10 and 30 minutes per plot to provide additional moisture on particularly warm and dry days.

2.7 SPRINKLER DISTRIBUTION PATTERNS AND RATES

The output rates and distribution patterns of the six sets of XP 300 sprinklers were tested by arranging 85 plant-pot saucers, of diameter 181 mm, over each plot, placing them on the corners and centres of each sub-sub-plot, and activating the sprinklers for 30 minutes. The direction and speed of any wind was noted every 2 minutes during the running time of the sprinklers. From this work the mean output rate of all the XP300 plot irrigation systems was found to be 7.0 mm hr^{-1}. A typical distribution pattern obtained from these data under still conditions is shown in Figure 2.5. Contours represent rate intervals of 1 mm hr^{-1}. The central low area with higher rates in the middle of each side represents a pattern produced by sprinklers projecting water less than the distance between the heads. The coefficient of variation of the data presented in Figure 2.5 was 22.4.

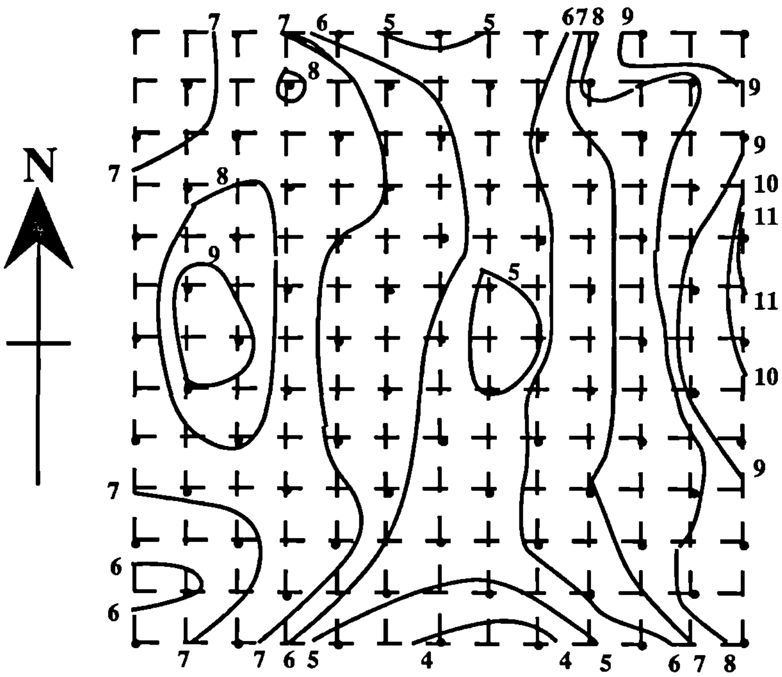

FIGURE 2.5

Typical distribution pattern of irrigation rates delivered by the XP 300 system under still conditions. Contours represent rate intervals of 1 mm hr^{-1}.
Mean delivery rate = 7.0 mm hr^{-1}.

The TORO Network 8000 System controlled irrigation times based on the manufacturers estimates of the TORO sprinkler head output rates. The measured output of the XP 300 systems was found to be only 61% of this. Therefore, during the period over which the

XP 300 heads were employed, the plots received only 61% of the theoretically derived water losses. This phenomenon, coupled with the excessive spacing of the heads and subsequent low coverage, led to serious underwatering during much of the establishment period. These effects were most severe in the centres of the plots and caused poor establishment of the turf, most notably on the sand-based constructions. It was therefore decided that the application of differential irrigation and fertiliser treatments should be delayed by one year, and that the sprinkler heads should be replaced by the more powerful TORO 640 heads.

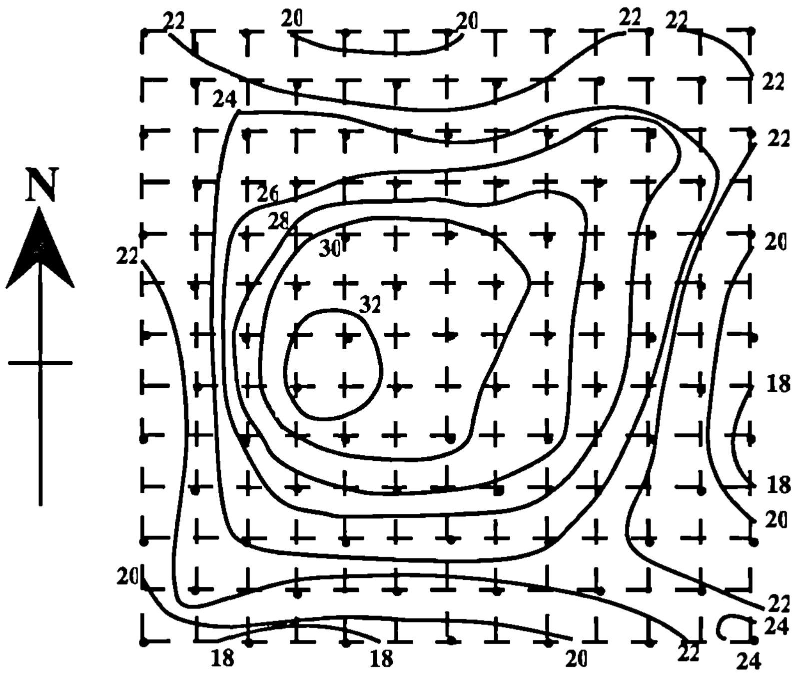

FIGURE 2.6

Typical distribution pattern of irrigation rates delivered by the 640 system under still conditions. Contours represent rate intervals of 2 mm hr^{-1}. Mean delivery rate = 24.3 mm hr^{-1}.

Each 640 head in the system was designed to project water as far as its neighbouring heads and this produced an overall mean output rate per plot of 24.3 mm hr^{-1}. The distribution patterns obtained were typified by that shown in Figure 2.6. This shows a high spot in the plot centres, with the rate declining from there outwards. The coefficient of variation of the data presented in Figure 2.6 was 16.8.

This pyramidal form of distribution was only obtained in absolutely still conditions. Wind-induced distortions of this would be expected to take place on most occasions the sprinklers were activated. After carrying out distribution tests on the same plot system at an average wind speed of 4.0 mph, the mean delivery rate to the plot fell to 22.2 mm hr^{-1}. This wind produced the distribution pattern shown in Figure 2.7. The coefficient of variation of these data was 14.2. When the same plot system was examined at a wind speed of 6 mph, mean delivery rate remained roughly unaltered at 22.7 mm hr^{-1}, but the coefficient of variation rose to 26.1. Another plot system had a coefficient of variation of 21.7 under still conditions, a figure which rose to 25.9 when tested at an average wind speed of 3.4 mph. The mean irrigation rate fell in this case from 25.1 mm hr^{-1} to 20.7 mm hr^{-1}.

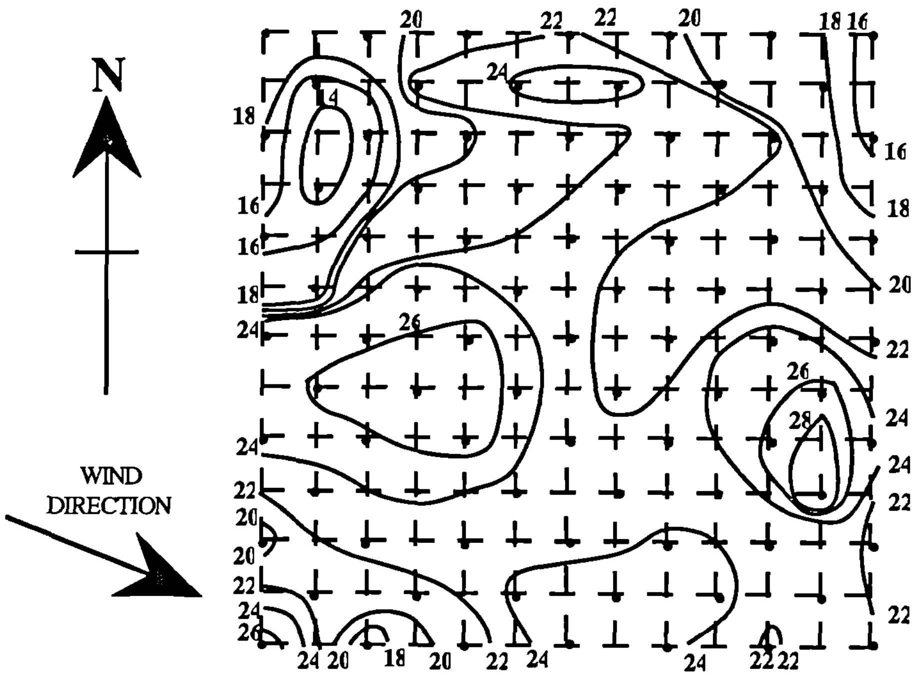

FIGURE 2.7

Typical distribution pattern of irrigation rates delivered by the same 640 system as in Figure 2.6 with a 4.0 mph wind blowing in the direction of the indicator arrow. Contours represent rate intervals of 2 mm hr^{-1}. Mean delivery rate = 22.2 mm hr^{-1}.

Continuous wind during sprinkler operation would tend to shift the pyramidal pattern (Figure 2.6) towards the downwind side of the system, and fragment the cumulative effect of the four sprinklers, producing smaller and more numerous peaks. A gusting wind would produce a combination of the distribution patterns induced by the high and low wind speeds. This investigation showed that any wind up to about 3 mph caused a fall in delivery rate to the area of concern, but did not greatly affect the uniformity of distribution. Indeed, it may even have improved it. However, wind-speeds greater than 4 miles per hour did significantly reduce uniformity.

Sprinkler distribution patterns were clearly very sensitive to changes in wind speed and direction. Such effects would have come into play almost every time the sprinklers were activated. The still-conditions pyramidal distribution pattern (Figure 2.6) presented the possibility of data analysis using a covariate of irrigation rate delivered to each sub-sub-plot within each plot. This possibility was rejected on the grounds that the frequency of irrigation treatment application and the shifting of the distribution pattern by the wind in each case would have brought about an adequate degree of uniformity *over time* in the extent to which each sub-sub-plot was irrigated. Departure from uniformity was otherwise accepted as a source of error buffered by the sub-sub-plot randomisation.

2.8 THE IRRIGATION TREATMENTS

The TORO Network 8000 system contained the facility to individually control the overall rate of irrigation delivered by each of the six pop-up systems. The imposition of the irrigation treatments to each plot was therefore achieved by stipulating the percentage of theoretical demand ET (TDET) that was to be replaced. Three irrigation treatments were selected, an under-watering treatment in which less than 100% of TDET was replaced (1), the straightforward replacement of TDET (2) and an over-watering treatment in which greater than 100% of TDET was replaced (3).

In 1990, the percentages of TDET selected to correspond with the treatment imposition were 1) 75%, 2) 100% and 3) 125%. This range produced only slightly significant variation in one of the factors measured and reported in the study (see Chapter 3) and this was probably due to two causes. Insufficient time may have elapsed for the treatments to take effect, and the chosen rates of the under and over-watering treatments may have been inadequately dissimilar. Since the primary ET figure was adjusted for rainfall **before** the final treatment values were calculated, then when rain fell, this tended to bring the under and over-watering demand ET figures closer to 100%. For example, in July 1990, the total irrigation applied to the three treatments was 22 mm, 29 mm, and 37 mm, corresponding to 76%, 100% and 128% of theoretical, rainfall-adjusted demand ET. Adding rainfall meant that the total amount of water reaching the three treatments represented 91%, 100% and 112% of demand, thus greatly reducing the range of the treatment. In wet months this phenomenon was even more pronounced.

Access to the computer programme in order to incorporate the rainfall lower down the TDET replacement calculation was not possible. Therefore, in order to induce treatment responses more effectively, in 1991 the percentages of TDET selected to correspond with the treatments were altered to 60%, 100% and 140%. At weekends the under-watering treatment plots were not irrigated at all. They were also provided with the facility to be covered with 14 m x 14 m "ripstop" plastic covers. These were utilised, during 1991, when heavy rain appeared imminent during normal working hours and overnight during weekdays when manpower was available to manoeuvre them. The time and duration of each covering was noted, and the durations kept to a minimum in order to avoid complexing irrigation responses with those brought about by the change of environment beneath the covers. In 1992, no occasions arose when the covers could practicably be utilised.

The irrigation treatments were applied between week 14 (April) and week 42 (October) 1990, week 15 (April) and week 42 (October) 1991 and week 19 (May) and week 39 (September) 1992. The durations of each irrigation were derived from weather data collected during the 24 hour period beginning and ending at 16:00 hours. From the onset of treatment irrigation until week 19 (May), irrigation took place at 17:00 hours to avoid frost damage caused by surface water freezing overnight. The remaining irrigations took place at 24:00 hours.

2.9 THE FERTILISER TREATMENTS

The rates of nitrogen (N1 to N5) were chosen to span the expected optima of all three construction types (Escritt and Legg 1969, Christians *et al.*. 1981, Lawson 1987). The rates were 35, 110, 235, 410 and 635 kg N ha^{-1} yr^{-1}. Nitrogen was applied in solution as a mix of 50% ammonium sulphate-N (Gem Gardening, Accrington) and 50% urea-N (Sinclair Horticulture and Leisure, Lincoln). The total amounts of nitrogen were divided into equal dressings and each dressing applied in about 6 l of water with a watering can fitted with a rose. Applications to each sub-sub-plot took place 9 times per year for sand constructions, 6 times for USGA constructions and 3 times for soils. The dates of the fertiliser treatment applications to each construction are shown in Table 2.4.

The two phosphate levels were chosen to induce either a deficiency or an adequate supply to the sward (Canaway *et al.* 1987). The rates applied were 0 (P1) and 50 (P2) kg P_2O_5 ha^{-1} yr^{-1}. Phosphate was applied in microgranular form as superphosphate (Gem Gardening, Accrington). It was applied by hand in one dressing in week 15 (April) 1990. The powder was thoroughly mixed with a few handfuls of sand top-dressing to improve the uniformity of distribution within each sub-sub-plot and to avoid losses to the wind. Cross contamination between adjacent sub-sub-plots during treatment fertiliser application was avoided by using a 2 m square, 400 mm high, open-bottomed wooden box.

WEEK NUMBER	SAND	USGA	SOIL
15 (April)	N, P	N, P	N, P
18 (April)	N	-	-
19 (May)	-	N	-
21 (May)	N	-	-
24 (June)	N	N	N
27 (July)	N	-	-
28 (July)	-	N	-
30 (July)	N	-	-
33 (August)	N	N	N
36 (September)	N	-	-
37 (September)	-	N	-
39 (September)	N	-	-

TABLE 2.4
Dates of treatment fertiliser application to each of the construction types in 1990, 1991 and 1992.

2.10 NITROGEN FERTILISER DISTRIBUTION PATTERNS

The uniformity of fertiliser distribution within the sub-sub-plots was of major importance. Seemingly trivial differences in the method of application could produce as great as six-fold variation in the rate of application within the 2 m square areas. Such inconsistencies could produce marked variations in the turf with respect to colour, vigour and botanical composition etc, representing a major source of error in turf assessment. It was also necessary that the method used was speedy enough to ensure that dressings to the whole trial or to each block could be completed in one day. This reduced the influence of temporal or climatic factors as sources of error during fertiliser application.

The use of an 8 l watering-can fitted with a rose had provided a satisfactory means of fertiliser application when used with the box in earlier work (Canaway *et al.* 1987, Lodge *et al.* 1990). In the present study, the highest rates of nitrogen fertiliser being applied were such that inconsistencies in distribution could produce local high-spots in which the rate became toxic to the grass. It was necessary therefore to examine the degree of uniformity of distribution produced by several variations in the route taken by the watering can over the sub-sub-plot in order to arrive at the most uniform distribution method.

During a dressing, fertiliser was applied in 6 l of solution from an 8 l watering can. The rose was pointed downwards and when held around 300 mm from the surface produced a spread of around 300 mm. Using this method, five routes over a 2 m square area for the can, containing water, were tried. Eighty-one saucers, as used in the irrigation distribution work (Section 2.7), were spread evenly over the ground in the open-bottomed box. Each route was repeated five times in order to obtain measurable quantities of water in each saucer. The five paths investigated are shown in Figure 2.8.

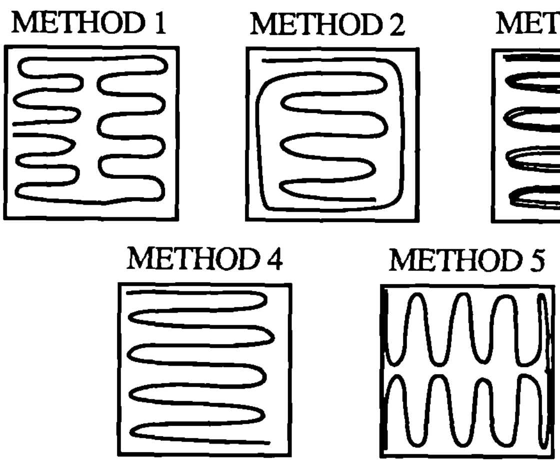

FIGURE 2.8
Methods of fertiliser application using an 8 litre watering can applied to a 2 m x 2 m area.

Table 2.5 shows the maximum percentage deviations from the mean volume of water collected by the saucers for the five paths investigated. From these data it was clear that Method 3 represented the most uniform distribution pattern and this was adopted for all dressings applied during this study.

DISTRIBUTION PATTERN	MAXIMUM DEVIATION (%)
1	49
2	78
3	30
4	55
5	65

TABLE 2.5
Maximum percentage deviation from the mean rate of "fertiliser" application within a sub-sub-plot for 5 different methods of distribution.

2.11 MAINTENANCE DURING TREATMENT APPLICATION

During the period of differential irrigation, nitrogen and phosphate application, potassium and magnesium were applied to the entire trial in the form of potassium chloride and magnesium sulphate. These nutrients were applied in solution at rates of 180 kg K_2O ha^{-1} yr^{-1} and 110 kg MgO ha^{-1} yr^{-1} in three dressings in weeks 15 (April), 24 (June) and 33 (August). Dressings were applied in solution using a spray boom mounted on a lightweight turf tractor.

A single dressing of a micro-nutrient fertiliser (Microcal ICI) was applied to all plots at a rate of 4 gm^{-2} in week 15 (April) 1990 and 1991. This fertiliser contained the following nutrients: S (15%); CaO (7.5%); Fe (12%); MgO (4.5%); Mn (2.5%); Zn (1%); Cu (0.5%); B (0.1%); and Mo (0.005%).

From week 36 (September) 1990 artificial wear was applied to the trial. The machine used for this purpose was a D.S. 2 wear machine, described by Canaway (1982). Two aspects of golf-type wear are simulated, the compacting pressure exerted by players standing on the surface, and the horizontal, abrasive action brought about when players walk or turn. The machine weighed 166 kg and had two sets of wheels mounted on separate front and rear axles. The horizontal, tearing forces were achieved by coupling the front and rear axles by pulleys of unequal size. This arrangement caused differential slip to occur between the two sets of wheels. The severity of the slip was determined by altering the ratio of the pulleys in the drive mechanism. Golf spikes were fitted to the wheels, the number of spikes per unit area corresponding to the numbers found on a typical golf shoe. The pulley ratio selected to simulate golf-type wear was 20 : 18 (Canaway 1982).

Wear treatments were carried out every week from week 36 (September) 1990 until the close of the trial period in week 43 (October) 1992, except when the area was considered unfit for play due to frost or snow. The numbers of weekly passes made with the machine during the treatment application programme are given in Table 2.6. These were chosen to simulate the seasonal changes in wear undergone by golf greens. Also given in Table 2.6 are the details of the mowing and mechanical maintenance procedures carried out during the experimental period.

Mowing	The height of cut was reduced from 8 mm to 6 mm in week 23 (June) 1990 and to 5 mm in week 26 (June) 1990. This was relaxed to 7 mm in week 48 (November). Mowing was carried out twice per week until week 22 (May). From then until week 42 (October) this was increased to 3 times per week. The height of cut was reduced to 5 mm in week 14 (April) and relaxed to 6 mm in week 43 (October).
Verticutting	The trial was lightly verticut once every fortnight from week 18 (April) 1990 to week 42 (October) throughout the experimental period.
Aeration	Aeration was achieved using slit tines of 150 mm in length fortnightly throughout the 1989-90 winter until week 17 (April). From then the slit tines were replaced by chisel tines of 100 mm in length used once per week until week 44 (November) when the deep slitting régime was resumed. This chisel / slit tine treatment was repeated throughout the experimental period.
Top dressing	Top dressing was applied to the trial on six occasions during the growing season at a rate of 1 kg m^{-2}. The sand sub-plots were treated with a medium-fine sand of similar particle size distribution and chemical analysis to the rootzone media. USGA and soil sub-plots were top dressed with a mix of the same type as the USGA rootzone. Top dressing was worked in using a hand lute.
Wear treatment	From week 36 (September) 1990, one pass per week until week 15 (April) when two passes per week were made. Between weeks 24 (June) and 39 (September) four passes per week were made, after which this was returned to one pass.

TABLE 2.6
Summary of trial management and wear treatments

2.12 DISCUSSION

The three construction treatments incorporated into the trial represent three widely differing growth media and the maintenance of turf on each demanded correspondingly different management procedures. For example, the verti-drain treatment was applied, during the establishment period, only to the soil constructions, because the SWT constructions exhibited no requirement for this. Similarly, in the treatment programme, fertiliser nitrogen was applied to the three construction types in three correspondingly different numbers of dressings (see Table 2.4). This was because, intuitively, the less the proportion of clay minerals and organic matter in the rootzone, the less the nutrient retention capacity, and hence the need to supply nitrogen in smaller, more frequent quantities throughout the growing season. Scientifically, this represents a departure from a purist approach. Effects attributable to the construction media alone could not be distinguished from those brought about by differential fertiliser dressing times or rates.

If fertiliser nitrogen had been applied to the entire trial in 9 dressings, as for the sand constructions, this would have been contrary to the normal practice pertaining to soil construction greens. It was therefore decided to consider each construction type as a package of construction-related factors. In practice, this simply involved considering the differential fertiliser application frequencies, top dressing applications, and the preliminary levels and infiltration rates adjustments as additions to the open-ended number of differences between the construction types investigated. The three construction treatments may however, in some circumstances, be considered as reresentatives of a continuum with respect to the amount of organic matter and clay minerals which contribute to the general buffering capacity of the rootzones.

The fertiliser treatment programme provided four periods when the amounts of fertiliser applied to each constuction type were the same. These were at the beginning and end of the growing season, and after one third and two thirds of the treatment fertiliser had been applied. Evaluation of the turf therefore usually took place during these periods in order to maintain the relevance of the treatment design.

One objective of the research was to describe the dynamics of water within golf greens, including its loss by evapotranspiration (ET). The commercial computer system utilised to predict ET water losses, and control the irrigation treatment programme, did so from locally obtained meteorological data (see Section 2.9). This predicted value in effect presaged any direct measurement of ET losses. Under UK conditions however, no comparison between measured and predicted values of ET from golf green turf have been carried out. This research therefore presented an opportunity to do so. Because no such comparison had taken place, the imposition of three irrigation treatments on the basis of a theoretical and un-tested measure of ET may seem inappropriate. The irrigation treatments imposed were therefore considered simply to represent under-, standard and over-watering of the turf. The term theoretically derived ET (TDET) was used to relate to the three irrigation treatments imposed.

The research objectives of the project, outlined in Section 1.10, indicate the manner in which the work is reported. The following three chapters address the treatment effects on the physical properties and water relations of the turf produced, ecological processes including botanical composition and rootzone chemical changes, and playing quality phenomena. The sixth chapter describes a method of using multivariate analysis techniques to collate information on turf quality and indicate appropriate management practices.

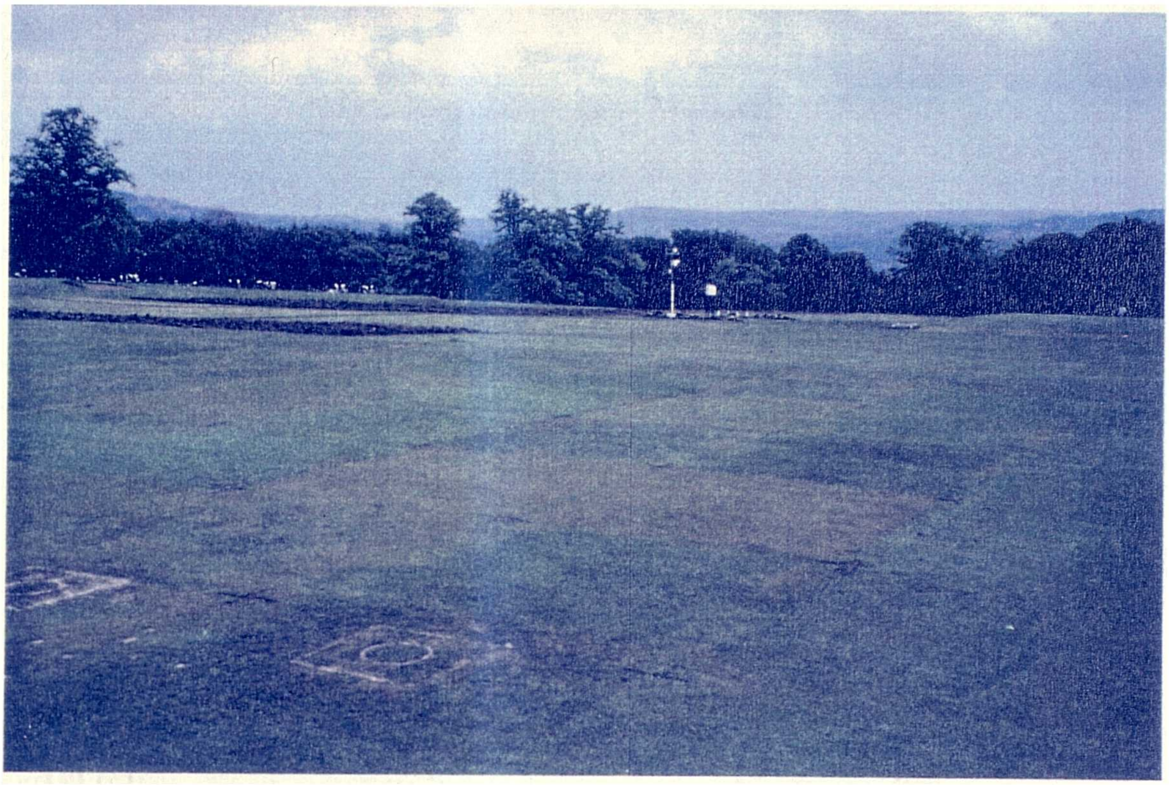

PLATE 1
View of the trial ground in the spring of 1990.

PLATE 2
View of the trial ground in the spring of 1992.

CHAPTER 3 - STUDIES IN WATER RELATIONS

3.1 INTRODUCTION

The basic objective of the irrigation of golf green turf is to use water to maintain the best possible surface in terms of visual and playing quality. In order for irrigation management to be most effective, the appropriate frequency of application and amount of water applied in each case needs to be known. In theory, these factors are dependent on the rate of loss of water by evapotranspiration, the amount of plant-available water the green construction or rootzone is capable of holding, and the speed with which water arriving at the surface is absorbed.

The concept of plant-available water is not readily defined. Veihmeyer & Hendrickson (1931) proposed that the "field capacity" could be considered as the upper limit of plant available water when gravitational drainage is not impeded. These workers also defined the lower limit as the "permanent wilting point" which represented the moisture content of the soil when the leaves of plants growing in it reached a stage of wilting from which they did not recover when placed in a saturated atmosphere without the addition of water to the soil (Hendrickson & Veihemeyer 1934). A major drawback of the permanent wilting point is that different plant species may indicate differing permanent wilting points in the same soil, due to inherent, specific differences in drought tolerance (Slatyer 1957).

This approach to the definition of plant-available water in golf greens may however retain some value. This is because the differing soil / construction types under consideration in this study support the same species maintained in basically the same growth form in each case. The concept of permanent wilting point came out of agricultural studies in which maintaining and improving yield was the main consideration. On golf green turf the maintenance of quality is the chief objective. For practical purposes then, the lower limit of desirable soil water content may be said to be that water content below which water availability restricts one or more aspects of turf quality. These considerations would indicate that the measurement of evapotranspiration (ET) and soil water content relative to field capacity, coupled with some form of quality evaluation, could provide the information necessary for deriving the optimum irrigation strategy for the three types of golf green construction under examination.

There have been two approaches to the measurement of evapotranspiration from close-mown turf. These are the water-balance and energy-balance methods which are discussed in general terms by Beard (1985). Most work on turfgrass ET has utilised the water-balance method. This is based upon the relationships described by the equation:

$$P - O - U - ET + \Delta W = 0 \qquad (4.1)$$

in which:

ET = evapotranspiration
ΔW = change in soil water storage during the specified measurement period
P = amount of precipitation
O = amount of runoff
U = amount of drainage beyond the rootzone.

Using this equation, P, O, U and ΔW are measured in order to derive ET by difference.

The water balance method of deriving ET has been successful in much recent turfgrass research using lysimeters (eg Feldhake *et al.* 1983, Johns & Beard 1981, Johns *et al.* 1983). Lysimeters are well suited for the monitoring of turfgrass ET due to the largely homogeneous nature, high shoot density and shallow rooting systems of the vegetation.

The energy balance method of measuring ET is founded on the work of Penman (1948, 1963), and incorporates the concept of potential evapotranspiration (PET). This is defined as the evaporation from an extended surface of short green vegetation that fully shades the soil surface, exerts little or no resistance to the flow of water, and is maintained under non-limiting water conditions. This definition applies to well irrigated turfgrasses and can be measured by recording the ambient weather conditions and the aerodynamic nature of the evaporating surface.

The Meteorological Office Rainfall and Evaporation Calculation System (MORECS) provide PET figures, measured by the energy balance method (Monteith 1981) for 40 x 40 km square areas of the UK for various crop plants, including grass mown at 150 mm. By altering a factor related to the bulk surface resistance term of the Penman-Monteith formula, the restrictive effects of increasing soil moisture deficits on ET are also accounted for, enabling MORECS to provide values of actual ET (AET). Aronson *et al.* (1987) tested a model, based on the Penman formula, for predicting ET losses from well - watered turfgrass mown at 50 mm. A small number of golf courses, located mainly in the USA and on the Continent, have incorporated on-site weather stations, like the one used to bring about the irrigation treatments (Section 2.6 vii), linked to computers which generate theoretical PET figures by similar means and can automatically control the delivery to sprinkler systems to replace predicted losses.

Actual ET can be measured using lysimeters. However, the lysimeter must adequately reflect the soil conditions supporting the turf, and the variability of the measurements obtained is very much dependent on its size. Tovey *et al.* (1969) described turfgrass ET and the moisture release characteristics of a sandy loam and a loam soil. These workers estimated ET using weighing lysimeters of between 1.0 and 1.8 m^3 in volume. Such apparatus may accurately monitor the water balance of the whole construction profile, but the procedure is too costly to provide data for the examination of more than one or two experimental treatments. Feldhake *et al.* (1983) measured turfgrass ET using very much smaller weighing lysimeters of only 0.012 m^3 in volume and 229 mm depth. The suspended water table design of golf greens (USGA 1989) relies on the existence of an interface, at a depth of 300 mm, between a sandy rootzone and a coarse sand blinding layer in order to bring about the water retention properties of the construction. A lysimeter designed to monitor ET and moisture content changes within such a profile must therefore be of a size to incorporate this interface.

Under UK conditions no direct measurements of very fine turfgrass ET have been made. Most work on turfgrass evapotranspiration has been carried out in the USA under climatic conditions and with turfgrass species that are not generally found in the UK. The appropriate use of ET prediction models for golf greens in the UK remains to be tested. In this study, ET was measured using small-scale weighing lysimeters. These were large enough to contain the entire rootzone and water retention elements of the construction types, but were of conveniently manageable size.

The regular weighing of lysimeters provides information regarding the changes in soil water content which may occur. Because each one can be saturated and allowed to drain freely, a value of field capacity may be obtained. When returned to the ground, subsequent weights may be expressed as the difference or the soil moisture deficit (SMD) in mm. This is useful since all the components of the water balance equation (Equation 3.1) may then be expressed in the same units. Also, the special, theoretical characteristics of the suspended water table (SWT) form of golf green construction may be examined. For a SWT construction, theory suggests that if irrigation is applied in excess of that required to lower moisture deficit to field capacity, the excess will be lost as drainage. If rainfall plus irrigation is equal to ET then the rootzone will be maintained at field capacity and if the inputs are less than the ET losses, then the rootzone will dry out. However, this theory has not been tested in the field.

Understanding of water loss from the rootzone may be enhanced by studying the rootzone structure and moisture release characteristics. This would enable the rootzone water content to be expressed as the the equivalent tension, or suction, with which the water is retained. This gives an indication of the difficulty which the turf experiences in actual water uptake. Thus, if the equivalent tension at field capacity were known, the lysimeter SMD values (in mm) could be translated into equivalent tensions (in kPa) using the characteristic moisture release curves of each construction. Rootzone structure and moisture release curves were therefore obtained in order to determine the water content of each rootzone at which water availability was likely to become limiting.

The effectiveness with which a golf green absorbs plant-available water is also governed by its infiltration rate. If this is appreciably less than the delivery rate, then ponding and runoff may occur, giving rise to a range of turf - related problems and even closure of the golf course. As was discussed in Section 1.3, rootzone texture and structure are of major significance in determining turfgrass infiltration rates, but other factors may also come into play. The infiltration rates of the three types of golf green construction were therefore compared over the trial period in order to establish the importance of this feature with respect to irrigation strategies.

3.2 MATERIALS AND METHODS

The measurement of soil moisture deficit (SMD)

In March 1990 small scale, bucket-type, weighing lysimeters were installed in each of the 36 destructive sampling plots (DSPs - Section 2.2). The design of the lysimeters is shown in Figure 3.1. They consisted of a 370 mm length of plastic drainage pipe (BS 4660 - outside diameter 249 mm), with a stainless steel mesh and nylon voile held across the bottom to facilitate vertical water movement but preventing loss of the solid contents of the lysimeter. The mesh was made of woven stainless steel wire, 1.6 mm thick with hole size 6.9 mm, and was screwed to a stainless steel retaining ring. The inner cylinder fitted closely inside an outer sleeve made of UPVC pressure pipe (BS 3505 - outside diameter 271 mm). The lysimeters were extracted from the sleeve by means of a purpose-built tool which hooked onto three lifting bolts situated at equal distances around the circumference of the top of the lysimeter (see top view, Figure 3.1).

The lysimeters contained a 350 mm deep core through the respective construction types (see side view, Figure 3.1). The cores, of 236 mm diameter, were extracted with minimal disturbance to the profile using an appropriately sized cutting tube. The depth of the cores were adjusted to fit the lysimeters by the addition or removal from the bottom

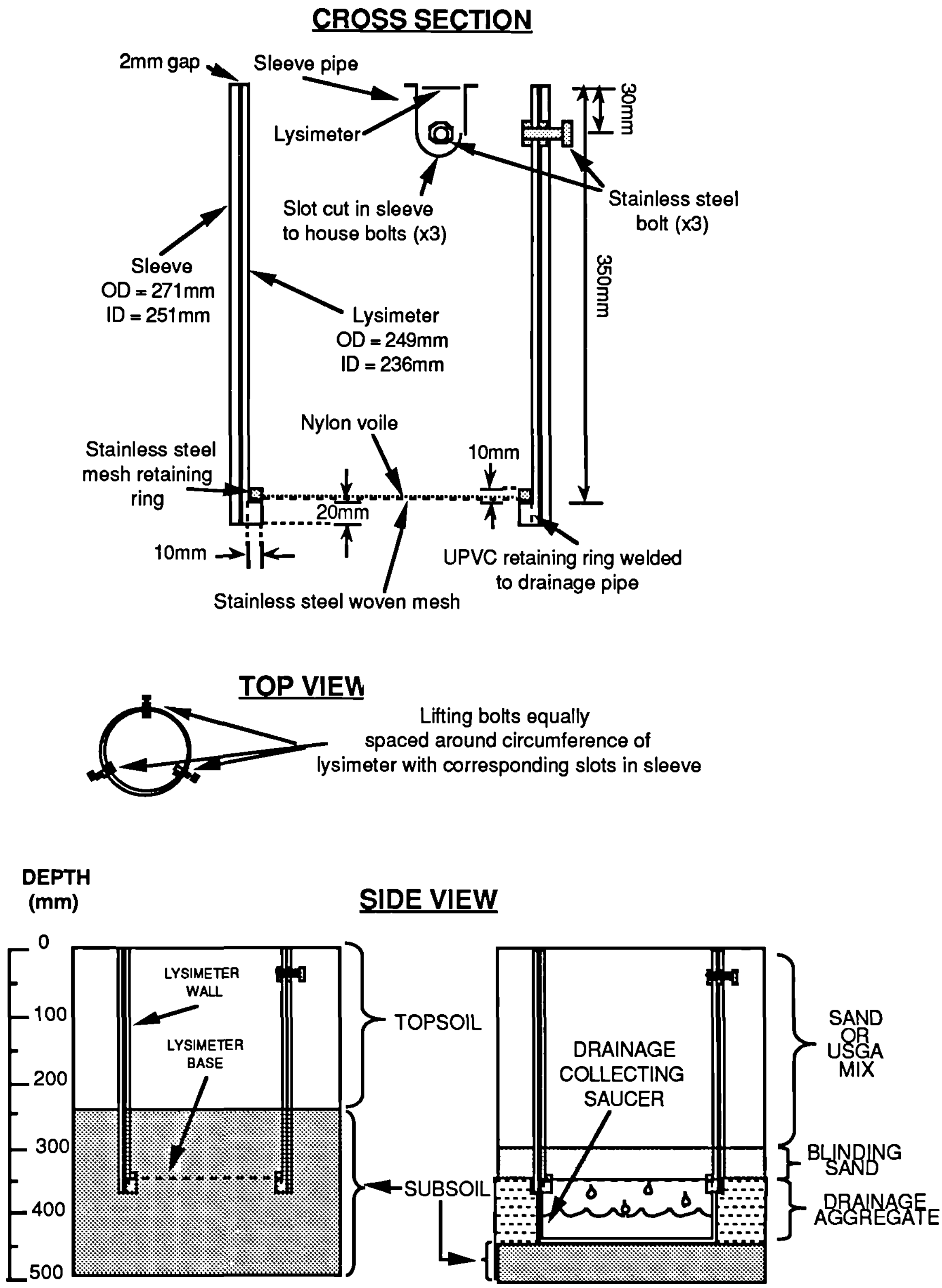

FIGURE 3.1
Cross section, top and side view diagrams illustrating the design of the lysimeters. (OD = outside diameter, ID = inside diameter).

of the cores of subsoil, in the case of the soil constructions, or blinding sand for the SWT constructions. After placing the mesh and voile over the bottom, the cores were then transferred into the lysimeter tubes and the lifting bolts installed. The holes made by the removal of the cores were widened to allow the insertion of the outer sleeve tubes which remained in position throughout the study.

In week 12 (March) 1992, drainage collecting saucers, of approximately 2.8 litre capacity, were placed beneath the lysimeters on the SWT constructions to collect water which passed down through the voile and mesh. These consisted of a plastic disc welded onto the bottom of a 65 mm length of the drainage pipe used for the manufacture of the lysimeters.

The saucers were not placed beneath the soil construction lysimeters for two reasons. Firstly, the collecting saucers would have broken the continuum between the lysimeter contents and the underlying subsoil. This would have prevented any capillary rise, or suction, originating from below and consequently made the soil lysimeters unrepresentative of the conditions in the surrounding turf. This break was already present on the SWT constructions in the form of the drainage aggregate carpet. Secondly, observations in the winter of 1991 / 1992 revealed that on the soil constructions a "water table" was formed, the height of which fluctuated between the rootzone surface and the subsoil throughout the wetter months of the year. Any collecting vessel would have become permanently full of groundwater whenever this water table rose above its rim at a depth of 370 mm.

The soil construction water table was not a true groundwater table as it did not affect the other two construction types. Water was held in the soil rootzone presumably due to impeded drainage. Its height was monitored using piezometer tubes set into the soil near each lysimeter. These consisted of 350 mm long plastic tubes (diameter 25 mm). The piezometers were inserted into previously bored holes lined with coarse sand. The water table height was recorded, at the time of each lysimeter weighing, by measuring the distance from the soil surface to that of the water which collected in the tube. The water was then removed with a syphon pump so that the water table equilibrated with the piezometers after each measurement.

The surfaces of the lysimeters were kept flush with the surrounding turf by regulating the amount of either subsoil or drainage aggregate upon which the lysimeter units rested. On the soil constructions, the level of subsoil was regulated to ensure a water continuum was maintained between the lysimeter subsoil and the underlying layer. This also permitted the uninterrupted imposition of the close-mowing, mechanical and wear treatment programme on the lysimeter turf, with the exception of the damaging aeration procedures using slit and chisel tines. The lysimeters were avoided when carrying out these operations.

The lysimeters were weighed to an accuracy of 2 g on an electronic balance (Ohaus, model IS45, capacity 45 kg) every seven days from week 24 (June) to week 47 (November) 1990, from week 20 (May) to week 43 (October) 1991 and from week 12 (March) to week 43 (October) 1992. The overall weight of each of the units was of the order of 32 kg.

In week 12 (March) 1992, the weight at "field capacity" of each lysimeter was found by immersing each one in water to within 1 or 2 mm of the top for 24 hours in the case of the soil constructions and 4 hours for the SWT constructions. The lysimeters were then weighed immediately, to obtain the saturated weight (W_{sat} in kg), then allowed to drain for 24 hours and reweighed to obtain the field capacity weight (W_{fc} in kg).

In week 22 (May) 1991, cylindrical cores of 80 mm length and 54 mm internal diameter were taken from each of the DSPs. One core was taken from each of four depths (10 - 90 mm, 90 - 170 mm, 170 - 250 mm, 250 - 330 mm) throughout the rootzone media and blinding layers of each DSP. This was achieved using a soil corer which was recessed to house the cylinders (Dagg & Hosegood 1962). The top 10 mm of the turf, which consisted almost entirely of grass, thatch and root material, was removed when the samples were taken. Bulk density (D_b) was calculated from the oven dry (105°C) mass of soil in each cylinder divided by the cylinder volume. On the soil construction types, high stone contents for depths below 250 mm (in the subsoil) meant core sampling was not possible. In consequence, the mean bulk density of the subsoil was established from three widely spaced locations on the paths surrounding the trial by the sand displacement method of Smith and Thomasson (1974). The bulk densities of the different layers in each DSP were then used to estimate the dry weight (DW) of the respective lysimeter contents. From this information, the actual moisture content (AMC) of each lysimeter (expressed as equivalent depth of water in mm) at field capacity (AMC_{fc}) was derived from Equation 3.2:

$$AMC_{fc} = (W_{fc} - DW - LW) \times 21.652 \qquad (3.2)$$

where LW is the weight of the empty lysimeter (established before installation). The saturated VMC (AMC_{sat}) was determined by adding the volume (in mm) of water lost over the 24 hour drain period to AMC_{fc}.

The soil moisture deficit (SMD), in mm, of the lysimeters was obtained from Equation 3.3:

$$SMD = (W_{fc} - W_{week}) \times 21.652 \qquad (3.3)$$

where W_{week} is the lysimeter weight (in kg) at the time of each weekly weighing.

On those occasions when a water table was present in the piezometers, the SMD values increased by a factor which was not a function of either the treatments or the general growth of the turf. In order to avoid the positive values of SMD which this created, a crude estimate of the SMD of the soil constructions was therefore calculated for the unsaturated region of each lysimeter above the indicated water level. This was achieved using Equations 3.4 to 3.7:

$$ws = ((h - pz) / h) \times W_{sat} \qquad (3.4)$$

$$wx = W_{week} - ws \qquad (3.5)$$

$$fcx = (pz / h) \times W_{fc} \qquad (3.6)$$

$$SMD = (wx - fcx) \times 21.652 \qquad (3.7)$$

where pz is the depth of the water table from the surface (in mm), ws is the weight of the saturated region (in kg), wx is the weight of the unsaturated region (in kg), fcx is the field capacity weight of the unsaturated region (in kg) and h is the height of the column of soil in each lysimeter (350 mm). Adjusted values of SMD were between 7 and 9 mm less than unadjusted values in weeks when SMD was within 10 mm of field capacity, and this difference fell to between 1 and 3 mm in the driest weeks.

The measured values of SMD were compared with the predicted figures for soil obtained from the Meteorological Office and applying to the 40 x 40 km square in which the trial was situated. These data are calculated using the Penman / Monteith prediction (Monteith 1981) of potential and actual evapotranspiration losses from grass of 150 mm height.

The measurement of evapotranspiration (ET) - water balance method.
Weekly weight changes were converted to millimetres by dividing by the lysimeter volume to give the equivalent change in the depth of water held in the lysimeter (ΔMC). At the time of each weighing, following the installation of the drainage collecting saucers in week 12 (March) 1992, the volume of water collected in each was removed with a stirrup pump, measured (in ml) and discarded. These values were then similarly converted to millimetres to give the drainage figures (D) for the calculation of ET.

From a knowledge of the mean delivery rate of each individual sprinkler system to the locations of each lysimeter (see Section 2.8), the cross sectional area of the lysimeters and the duration of each of the daily irrigations, the theoretical total amount of irrigation water (I) reaching the lysimeters during each weekly period was computed. The rainfall (P) which fell between weighings was also noted. The slope of the trial was only 1.25 %, so net runoff was assumed to be zero. The measured weekly evapotranspiration (ET_m), in mm week^{-1}, was therefore calculated as:

$$ET_m = ((P + I) - D - \Delta MC) \times (7/n) \qquad (3.8)$$

where n is the number of days between measurements (usually 7).

The measurement of ET - energy balance method
Values of ET_m were compared with the appropriate Penman / Monteith prediction (Monteith 1981) of potential and actual evapotranspiration losses from grass of 150 mm height (ET_{pMet} and ET_{aMet}) as issued by the Meteorological Office. In addition, the mean daily wind speed, mean and minimum daily air temperature, and daily total solar radiation, provided by the on-site weather station, were used to derive a prediction of PET ($ET_{Aronson}$) using a model based on that described by Aronson *et al.* (1987). A summary of this method is provided below.

The model was based on the modified Penman equation (Burman *et al.* 1980, Penman 1948), and the exact form of the equation used was:

$$ETE = \frac{\Delta}{\Delta + \gamma}(Rn + G) + \frac{\gamma}{\Delta + \gamma} 15.36 \, wf \, (ea - ed) \qquad (3.9)$$

where ETE = energy available for vapourisation of water in J m^{-2} day^{-1}; Δ is the slope of the vapour pressure - temperature curve in kPa °C^{-1}; γ is the psychrometer constant (from Penman 1948) = 0.11915 kPa °C^{-1}; Rn is net radiation in J m^{-2} day^{-1}; G is heat flux to the soil in J m^{-2} day^{-1} (assumed to be zero on a daily basis); wf is the wind function (dimensionless); and (*ea* - *ed*) is the mean daily vapour pressure deficit in kPa. ETE was converted to mm day^{-1} (or mm $week^{-1}$) using the latent heat of vapourisation at the mean daily temperature.

The wind function (wf) (Schwab *et al.* 1985) used was :

$$wf = 1.0 + 0.00621\, U_2 \qquad (3.10)$$

where U_2 is the wind velocity (km day^{-1}) at a height of 2 m.

The saturation vapour pressure (svp) at daily mean air temperature was used for *ea*, and at the mean daily dewpoint temperature for *ed*. The dewpoint temperature was set equal to the daily minimum temperature (Merva & Fernandez 1985). The svp (in kPa) for a given temperature (in °C) was calculated by the approximation of Bosen (1960) as reported in Burman *et al.* (1980). This is shown by Equation 3.11:

$$svp = 3.38639\, [(0.00738T + 0.8072)^8 - 0.000019|1.8T + 48| + 0.001316] \qquad (3.11)$$

where T is the temperature of interest in °C.

Net radiation (R_n) was calculated from the expression of Schwab *et al* (1985):

$$R_n = (1 - r)R_s - \sigma T_a^4\, (0.56 - 0.08\sqrt{ed})\, (0.10 + 0.9n/N) \qquad (3.12)$$

where r = albedo (set at 0.23), Rs is incoming solar radiation (J m^{-2} day^{-1}), T_a is the mean daily air temperature (°K), σ is the Stefan-Boltzmann constant. Daily records of incoming solar radiation were coupled with extraterrestrial radiation (from Smithsonian tables) to obtain estimates of n/N (the ratio of actual to possible hours of sunshine).

On-site meteorological data were obtained from the automatic weather station (Section 2.6 vii), using instruments provided by Campbell Scientific Inc. Solar radiation was measured with a LiCor solar radiation sensor, temperature using an electronic temperature probe and wind speed with an R.M. Young Wind Sentry.

The ET estimate provided by the unspecified and inaccessible software of the on-site computer (ET_{TORO}) was also examined.

Structure and moisture release characteristics

Prior to the calculation of bulk density (D_b) as described above, moisture release characteristics were measured for the cores collected from each of four depths from the DSPs in week 22 (May) 1991. Similar cores were also taken in week 10 (March) 1990, prior to the application of wear and of differential nitrogen and irrigation treatments. On this occasion, only the 10 - 90 mm depth was sampled, and 2 samples were taken from each DSP.

The core contents were held in place within the cylinders using a disc of voile held with a rubber band. Field and saturated core weights were obtained before placing the cylinders on a ponded, sand tension table (van der Haarst & Stakman 1965, Hall *et al.* 1977). Cylinders were allowed to equilibrate for 4 days before weighing at 0 kPa moisture potential and returning to the ponded tension table. The moisture potential was then decreased and the process repeated. The cylinders were weighed after equilibration at -1.5, -3.0, -4.5, -6.0, -7.5 and -9.0 kPa (i.e. at tensions of 0.15, 0.30, 0.45, 0.60, 0.75 and 0.90 m) Water potential was then increased and the process repeated, ascending through the same steps.

The equivalent pore diameters (d - in m) corresponding to the applied tensions (h - in m) were related by the formula (Payne 1988):

$$d = 3 \times 10^{-5} / h \qquad (3.13)$$

The mean bulk density and stone content of the subsoil was established from three widely spaced locations on the paths surrounding the trial by the displacement method of Smith and Thomasson (1974). Particle density (D_p) of the cylinder samples was calculated by the organic matter content method of van Wijk & Beuving (1984), using the equation:

$$D_p = \frac{100}{(z/D_{om}) + ([100-z]/D_{mm})} \qquad (3.14)$$

where:

D_{om} = true density of the organic matter component (1.46 t m^{-3})

D_{mm} = true density of the mineral matter component (2.66 t m^{-3}).

Organic matter content (z in percent) was determined by loss on ignition (Baker 1985). Particle density of the subsoil samples were measured by the specific gravity method

(Smith & Thomasson 1974). The percentage total porosity (P_{tot}) of each cylinder sample was then calculated as:

$$P_{tot} = (1 - D_b / D_p) \times 100 \quad (3.15)$$

The water content of the cylinders at the various moisture potentials was expressed as the percentage soil volume or volumetric moisture content (VMC - %). This was calculated as:

$$VMC = (W_i - W_d) / V) \times 100 \quad (3.16)$$

in which W_i is the sample weight at the specified tension (in g) and W_d is the oven dry mass of the core (in g) and V is the cylinder volume (in ml).

Infiltration rates

In week 26 (June) 1989, week 37 (September) 1989, week 11 (March) 1990, week 10 (March) 1991, and week 11 (March) 1992, the rate of infiltration of standing water on the surface of the DSPs was measured by the method of Schmidt (1980) described in Section 2.6 vi. Five such measurements were taken from each DSP, and the analysis performed on the mean of these.

3.3 RESULTS

Soil Moisture Deficit (SMD)

The saturated and field capacity water status of the lysimeters were measured after two seasons of differential nitrogen and irrigation treatments. Possible treatment effects were therefore examined and AMC_{sat} was found to differ significantly between constructions. AMC_{fc} did not significantly differ. The AMC data are shown in Table 3.1. The greatest loss of water between the saturated state and field capacity was shown by the USGA construction which lost 24 mm. The sand and soil constructions lost 9 and 11 mm respectively.

The SMD data were expressed in relation to the individual field capacity figures of each lysimeter (Equations 3.3 to 3.7). In 1990, no significant interactions between irrigation and construction were observed for SMD measurements. In 1991, irrigation treatments produced the same SMD trends as were observed in 1992 and these data were described by Lodge & Baker (1992). The mean SMDs of the three construction types for 1990 and 1991 showed that the soil construction consistently maintained the lowest SMD (ie least negative - the water content was greater) and the USGA construction maintained the highest (ie more negative - the water content was less). The amplitude of seasonal fluctuation in SMD was of the order of 45 mm on the soil constructions and 60 mm on the SWT constructions in both years. Because the piezometers and drainage collecting saucers were not installed until the begining of the 1992 season, and the main area of interest was in the irrigation treatments, the bulk of this section deals with data collected in 1992.

CONST.	AMC_{fc}	AMC_{sat}
SAND	129	138
USGA	144	168
SOIL	131	142

TABLE 3.1.
Actual moisture content (in mm) at field (AMC_{fc}) and saturated (AMC_{sat}) capacity of the lysimeters on the three construction types measured after two seasons of differential nitrogen fertiliser and irrigation treatment. The LSD ($p \leq 0.05$) for the main effect of construction on AMC_{sat} was 19 mm. AMC_{fc} did not significantly differ.

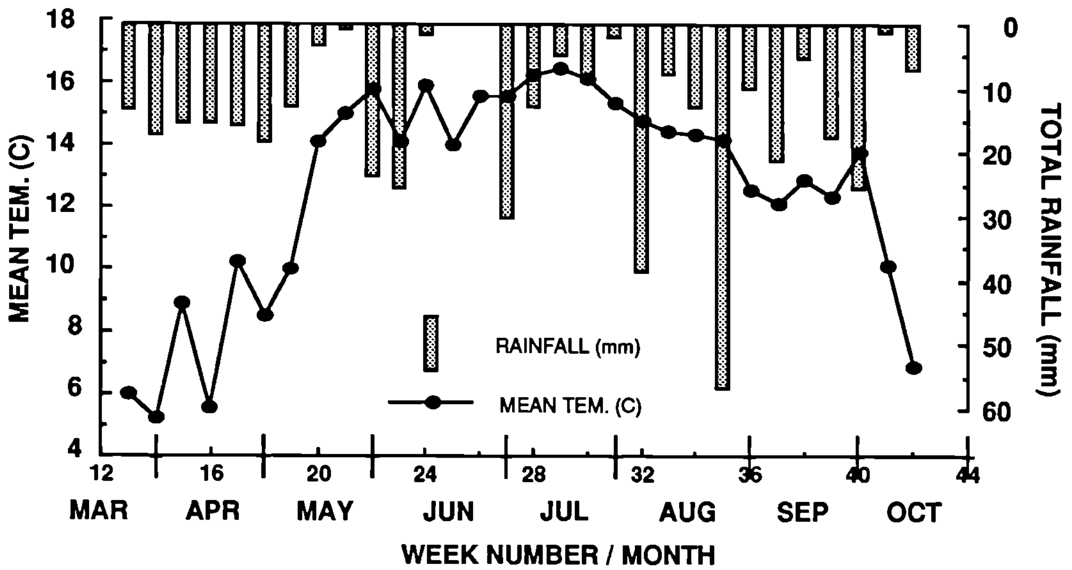

FIGURE 3.2
Mean weekly temperature (°C) and total rainfall for each week of the 1992 measurement period.

The total rainfall and mean weekly temperature for each week throughout the 1992 measurement period are shown in Figure 3.2. The total amount of irrigation supplied to the lysimeters of each of the three treatments over the 1992 measurement period were 72 mm (60% TDET), 122 mm (100% TDET) and 170 mm (140% TDET). The upper and lower figures represent 59% and 139% of the 100% TDET amount respectively, corresponding closely to the intended treatment programme. The total amount of rainfall over this period was 275 mm. This had the effect of reducing the degree of difference between the irrigation treatments to 87% and 112% of TDET for the lower and upper irrigation treatments respectively. The distinction between the irrigation treatments was therefore most apparent during dry periods.

The nitrogen fertiliser treatment had no significant effect on SMD either as a main effect or in interaction with the construction and/or irrigation treatments. The mean SMDs of the sand, USGA and soil (adjusted for water table fluctuation) construction types in response to the irrigation treatments applied during the 1992 measurement period are shown in Figure 3.3. The general seasonal trends shown by the SWT constructions were very similar. A large increase in SMD in week 20 (May) coincided with a sharp rise in temperature (Figure 3.2). Similarly, a sharp fall in SMD in week 35 (August) coincided with an exceptionally high rainfall (Figure 3.2).

Differential irrigation treatment responses became apparent (though not significant) on the SWT constructions less than two weeks after the onset of treatment in week 19 (May). The SMD was consistently greater for the 60% TDET treatment on both SWT constructions throughout the measurement period. On the sand constructions, the SMD response to the 140% TDET replacement treatment was almost identical to that of the 100% TDET treatment. On the USGA construction the same was true from around week 37 (August), although during most of the treatment period the 140% TDET treatment showed slightly lower SMD values.

The highest SMD was observed in week 26 (June). The effects of the irrigation treatments on SMD of the three construction types on this occasion are shown in Table 3.2. On the soil constructions, SMD was significantly less than that of the SWT constructions for all irrigation treatments. The 140% TDET treatment gave a lower SMD than the 60 and 100% treatments on all three construction types. On the sand constructions, the overall mean SMD was not significantly different from that of the USGA constructions, and the effects of the 100 and 140% TDET treatments did not significantly differ. On the USGA constructions, the three increasing irrigation treatments brought about three decreasing SMDs.

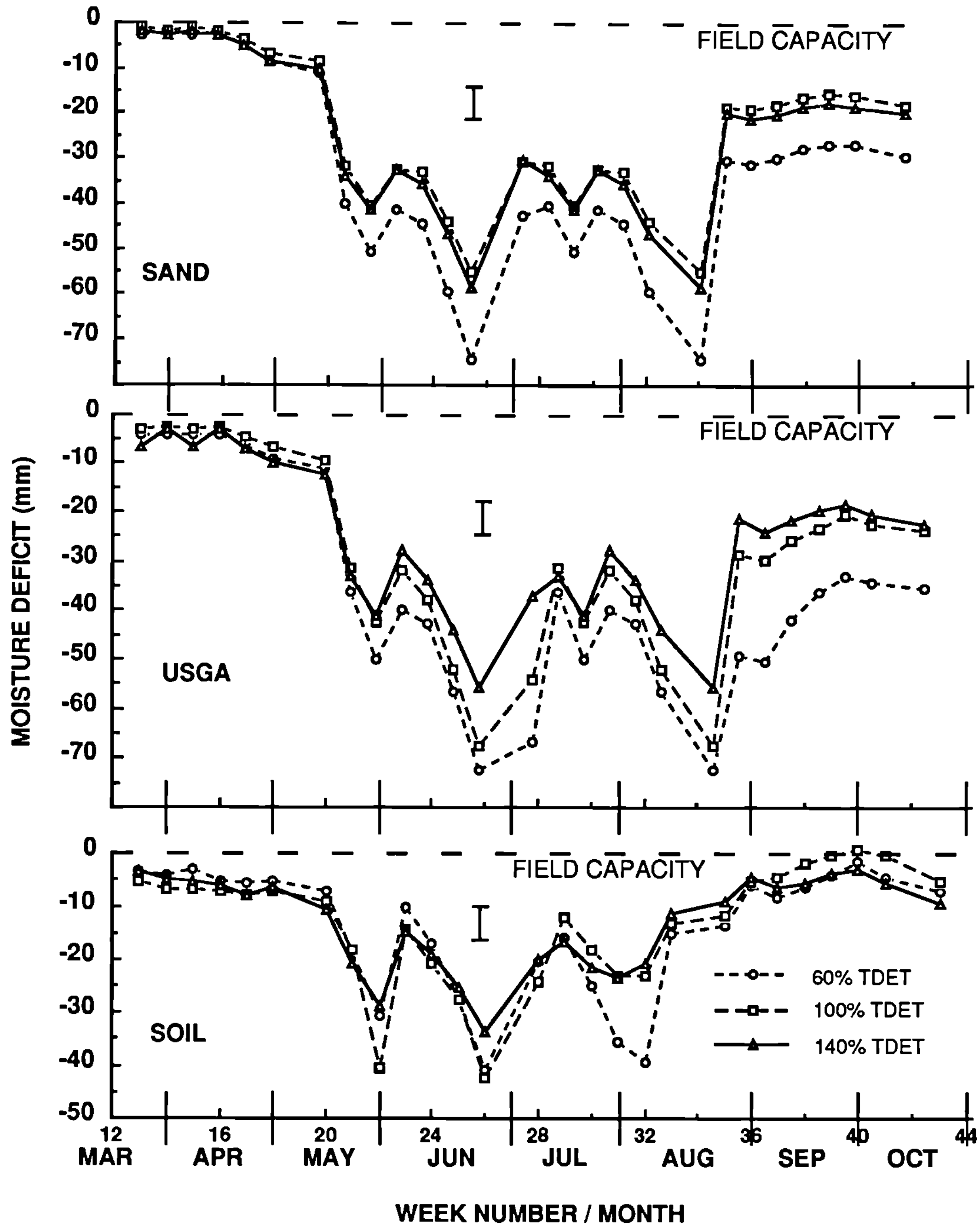

FIGURE 3.3

The effects of three different rates of irrigation on SMD (mm) on the three construction types over the 1992 measurement period. Vertical bars represent the LSD ($p \leq 0.05$) between irrigation treatments for each construction type upon the same date.

IRRIGATION TREATMENT	CONSTRUCTION TYPE		
	SAND	USGA	SOIL
60% TDET	-74.3	-72.2	-40.7
100% TDET	-55.0	-67.5	-42.5
140% TDET	-58.5	-55.8	-33.5
MEAN	-62.6	-65.2	-39.0

TABLE 3.2
The effects of three irrigation treatments on SMD (mm) of the three construction types in week 26 (June) 1992, the lowest values observed throughout the measurement period. LSD for the construction x nitrogen interaction was 8.5, and for the main effect of construction 5.9.

By week 43 (October), one month after the end of irrigation treatment, both SWT constructions maintained a steady state which was arrived at after the heavy rain of week 37 (August), but the 60% TDET treatments continued to show the greater SMD (Figure 3.3). This state was around -20 mm for the 140% and 100% TDET treatments on both SWT constructions, and around -30 mm on the sand construction and -35 mm on the USGA construction for the 60% TDET treatment.

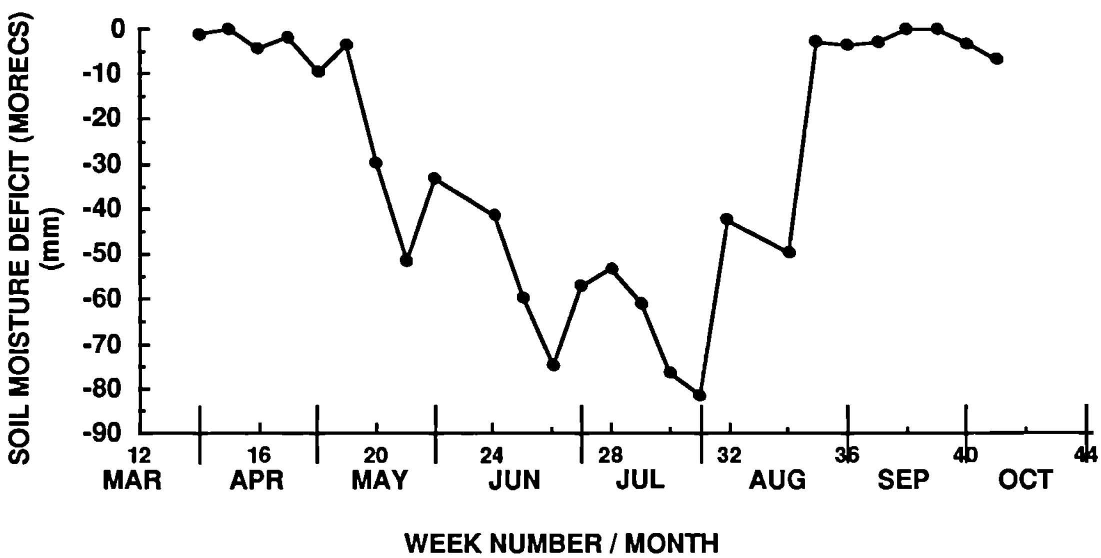

FIGURE 3.4
MORECS prediction of soil moisture deficit (mm) for the 1992 measurement period for the 40 x 40 km square in which the trial was situated.

The general seasonal variation in the SMD of the soil constructions followed essentially the same pattern as the SWT constructions. From week 32 (August) to the end of September, SMD showed a gradual return to field capacity status. The irrigation treatments had no significant effects, although the greatest SMD, in week 26 (June), was 8 mm less (-32 mm) on the 140% TDET treatment than that of the 100% and 60% TDET (-40 mm).

The MORECS estimates of SMD for the corresponding period are shown in Figure 3.4. The seasonal variation followed the same general pattern as that of all three construction types, but the scale of variation was most comparable with that of the 60 % TDET treated SWT constructions. By week 35, the MORECS prediction of SMD had returned to within 10 mm of field capacity (0 mm).

Evapotranspiration (ET)

During the measurement of ET_m, errors arose after wet weather which were most probably attributable to the measurement of "D" with the drainage collecting saucers. When the drainage volumes exceeded the capacity of the saucers (about 62 mm) and overflowed, the value of D was underestimated, giving an exaggerated value of ET_m. An arbitrary figure of 50 mm was therefore chosen so that when D exceeded this, the individual lysimeter data were discarded from the calculations. Similarly, on occasions after wet weather, the values of D for some lysimeter units were found to be excessively high, indicating that water may have entered the saucers by means other than drainage through the lysimeters. Runoff water, for example, may have run down the outside of the lysimeters and entered the saucers. This phenomenon tended to give values of ET_m which were negative. When this occurred the individual, negative, ET_m measurements were discarded (ie when ET_m was found to be less than zero). Discarding was carried out on 119 of the 624 data points in the 1992 measurement experiment. Of these, 64 were recorded in the particularly wet period between weeks 35 (September) and 43 (October).

Having made these omissions from the data, the mean weekly evapotranspiration of the two SWT constructions, derived by the water balance method (Equation 3.8), from the 1992 measurement period is shown in Figure 3.5 (ET_m). Also shown are the predictions derived by the Aronson method ($ET_{Aronson}$), the MORECS (ET_{Met}) and the on-site TORO system (ET_{TORO}). No significant differences in ET_m in response to the construction, irrigation or nitrogen fertiliser treatments were found.

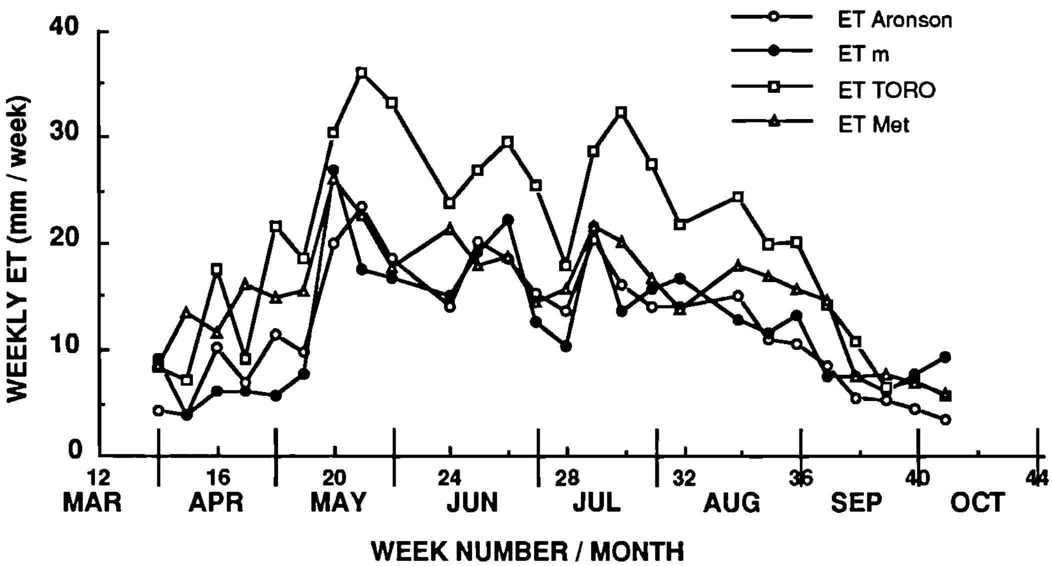

FIGURE 3.5

Weekly evapotranspiration rates (mm week^{-1}) measured for 5 mm turf (ET m) and ET predictions by MORECS for 150 mm grass in the 40 x 40 km square in which the trial was situated (ET Met), by the Aronson method (ET Aronson) and by the TORO computer software (ET TORO) over the 1992 measurement period.

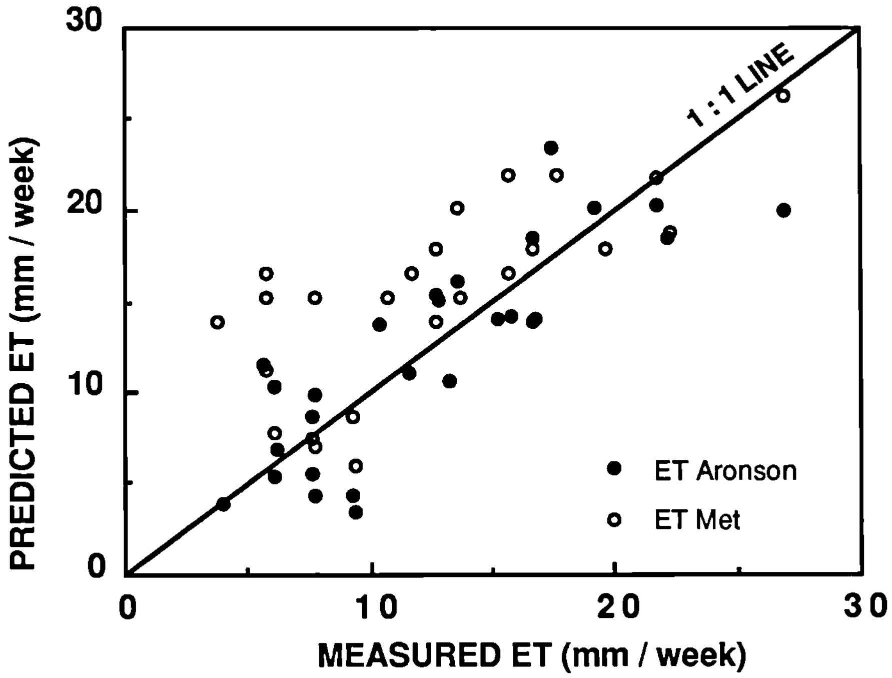

FIGURE 3.6

Scattergram of measured weekly ET (ET m) against the corresponding Aronson (ET Aronson) and MORECS (ET Met) predictions (mm week^{-1}).

All methods followed broadly the same seasonal pattern. The mean weekly ET_m rate was 16.0 mm week^{-1}. The mean ratio of ET_{TORO} to ET_m over this period was 1.48, and of ET_{Met} for 150 mm grass to ET_m was 1.42. The $ET_{Aronson}$ prediction corresponded more closely with ET_m, the corresponding ratio being 0.90. The relationships between ET_m and $ET_{Aronson}$ and ET_m and ET_{Met} are shown in Figure 3.6. The Aronson prediction gave close agreement throughout the range of measurements, while the exaggerated estimates of the Meteorological Office prediction showed the greatest discrepancy in the lower values.

Drainage losses from both constructions took place at periods and with magnitudes corresponding closely with those of the sum of irrigation and precipitation. The differential effects of the irrigation treatments on the total drainage losses from the two SWT construction types during the entire 1992 irrigation treatment period, and over the 8 ("dry") weeks of the measurement period when rainfall was less than 5 mm, are shown in Table 3.3. These data show that drainage losses from the USGA construction were higher than from the sand for the 140% TDET irrigation treatment both throughout the treatment period, and during dry periods when the treatments were the most distinct.

IRRIGATION TREATMENT	ALL WEEKS		DRY WEEKS	
	SAND	USGA	SAND	USGA
60% TDET	72	71	3.4	2.4
100% TDET	210	232	13.1	12.7
140% TDET	326	433	16.7	45.2

TABLE 3.3.

The effects of the three irrigation treatments on total depth of water (mm) lost through drainage on the sand and USGA construction types for the entire treatment irrigation period of 1992 and for the 8 of those weeks when rainfall was less than 5 mm (dry weeks).

Structure and characteristic moisture release curves

The effects of the nitrogen fertiliser treatment on porosity and characteristic moisture release curves were slight and are not described here. The irrigation treatments had no effects on any of the features described below.

The total porosity of the three construction types from the 10 - 90 mm depth cores on the two sampling dates are shown in Table 3.4. Total porosity was lower on all three construction types at the later date. This reduction was most marked on the soil constructions, the total porosity of which fell by 4.7 percentage points over the 13 month period during which wear and differential irrigation and fertiliser treatments were applied.

	CONSTRUCTION TYPE			LSD
	SAND	USGA	SOIL	($p \leq 0.05$)
March 1990	42.0	43.3	45.2	0.93
May 1991	40.6	42.3	40.5	1.43

TABLE 3.4

Total porosity (%) of the 10 - 90 mm depth of the three construction types in March 1990 (before the application of wear and differential nitrogen fertiliser and irrigation treatments) and in May 1991.

The reduction in total porosity on the SWT constructions was considerably smaller and in all cases there was no significant responses to the irrigation treatments. At the 170 - 250 mm sample depth, which frequently incorporated subsoil, total porosity of the soil constructions was 36.3%. This was significantly less ($p \leq 0.05$) than the porosity of the two shallower samples.

The organic matter content and bulk densities of the 10 - 90 mm cores on the two sampling dates are shown in Tables 3.5 and 3.6 respectively. Organic matter content increased slightly over the treatment period and was greatest on the soil and least on the sand constructions. At the 170 - 250 mm sample depth, organic matter content of the soil was 3.5 %. This was significantly lower (LSD [$p \leq 0.05$] = 0.57) than that of the shallower sample depths.

The bulk density of the soil constructions increased over the treatment period, while that of the SWT constructions showed little change. At the 170 - 250 mm sample depth, bulk density of the soil was 1.65 t m^{-3}. This was significantly greater (LSD [$p \leq 0.05$] = 0.03) than that of the shallower sample depths.

	CONSTRUCTION TYPE			LSD
	SAND	USGA	SOIL	($p \leq 0.05$)
March 1990	0.2	1.6	5.5	0.94
May 1991	0.8	1.8	5.6	0.68

TABLE 3.5

Organic matter content (%) of the 10 - 90 mm depth of the three construction types in March 1990 (before the application of wear and differential nitrogen fertiliser and irrigation treatments) and in May 1991.

	CONSTRUCTION TYPE			LSD
	SAND	USGA	SOIL	($p \leq 0.05$)
March 1990	1.54	1.49	1.40	0.94
May 1991	1.57	1.51	1.51	0.68

TABLE 3.6

Bulk density (t m^{-3}) of the 10 - 90 mm depth of the three construction types in March 1990 (before the application of wear and differential nitrogen fertiliser and irrigation treatments) and in May 1991.

During the 1991 assessment, the VMC values at the lowest moisture potential (-9.0 kPa) showed an increase with respect to the -7.5 kPa moisture potential values. This erroneous phenomenon was probably due to the entry of air into the tension table, breaking the continuity of the applied suction. The -9.0 kPa values were therefore omitted from the data that were presented. Returning the cylinders to a tension of 0 kPa brought about only a slight increase in VMC on all construction types, most of which occurred between -3.0 and 0 kPa moisture potential.

The VMC of the 10 - 90 mm depth samples of the three construction types on both sampling dates at the suctions applied with the tension table are shown in Figure 3.7. The individual responses of the three construction types were generally very similar on both sampling dates. At -4.5 kPa moisture potential, the sand and USGA constructions had lost around 69 % and 64 % of their saturation capacity (assumed to be total porosity) respectively. By -7.5 kPa tension, these values had increased to 80 % and 70 %. The soils lost 11 % of their saturation capacity by -4.5 kPa moisture potential and by -7.5 kPa this had increased to 16 % of saturated capacity.

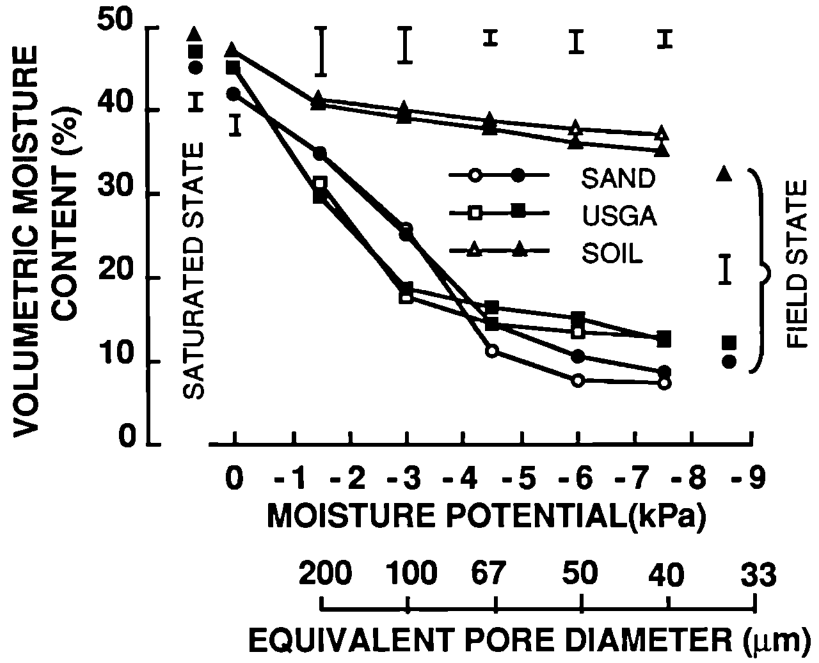

FIGURE 3.7

Volumetric moisture content (VMC) of the 10 - 90 mm sample depths of the three construction types at moisture potentials of between 0 and - 7.5 kPa. Open and solid markers refer to the week 11 (March) 1990 and the week 22 (May) 1991 assessments respectively. Also shown are the saturated and field states from the 1991 assessment. Vertical bars represent LSDs ($p \leq 0.05$) for comparisons between construction types in 1991. The corresponding LSDs from 1990 were all appreciably smaller and have therefore been excluded from the figure.

Also shown in Figure 3.7 are the saturated and field moisture content of the soil in the cylinders and the field moisture content at the time of sampling in week 22 (May) 1991. The saturated values were slightly higher on all three construction types than the corresponding total porosity values given in Table 3.4.

The data presented in Figure 3.7 were expressed as the percentage of total pore space of differing size classes and these are shown in Table 3.7. The most notable change was a reduction in pore spaces greater than 200 μm diameter on the soil constructions, while the proportion of the pore spaces less than 40 μm diameter increased. Pore size class distribution remained relatively constant on the USGA constructions, while on the sand constructions, the 100 - 67 μm diameter class showed a slight shift to the less than 40 μm diameter class.

PORE DIAMETER (µm)	SAND		USGA		SOIL	
	1990	1991	1990	1991	1990	1991
> 200	17	14	28	30	9	0
200 - 100	22	24	31	26	2	4
100 - 67	35	26	7	6	3	3
67 - 50	8	8	3	3	2	4
50 - 40	1	3	2	6	1	2
< 40	18	25	30	29	82	87

TABLE 3.7
Percentage of pore spaces in each diameter range (µm) of the 10 - 90 mm depths of sample from the three construction types in week 10 (March) 1990 and week 22 (May) 1991.

DEPTH (mm)	CONSTRUCTION TYPE		
	SAND	USGA	SOIL
10 - 90	10.9	12.0	31.9
90 - 170	10.4	11.2	29.7
170 - 230	14.9	11.0	26.8
230 - 310	19.9	13.4	-
MEAN	14.0	11.9	29.5
SMD (mm)	-38.3	-49.2	-12.3

TABLE 3.8.
Field condition VMC (%) of the three construction types at the four sampling depths in week 22 (May) 1991, and the corresponding SMD (mm) as measured with the lysimeters. LSDs ($p \leq 0.05$) for the VMC measurements were 3.13 for the construction x depth interaction, 2.57 for the main effect of construction, and 7.61 for the SMD measurements.

The variation in VMC of the three construction types with depth of sample in the field condition is shown in Table 3.8. Also shown are the corresponding SMD values obtained from the lysimeter measurements for the sampling period (week 22 (May) 1991. These data show a slight increase in water content at the bottom of the sand construction and towards the surface of the soil construction. Water content down the USGA construction was more or less uniform. The overall water content was lowest on the USGA construction and highest on the soil. The relative VMC values of the three construction types showed the same relationships to one another as the corresponding SMD values.

Infiltration rates

The infiltration rates of the SWT constructions were between 30 and 50 times greater than those of the soil constructions on all assessment dates. The data for the two were therefore presented in separate figures.

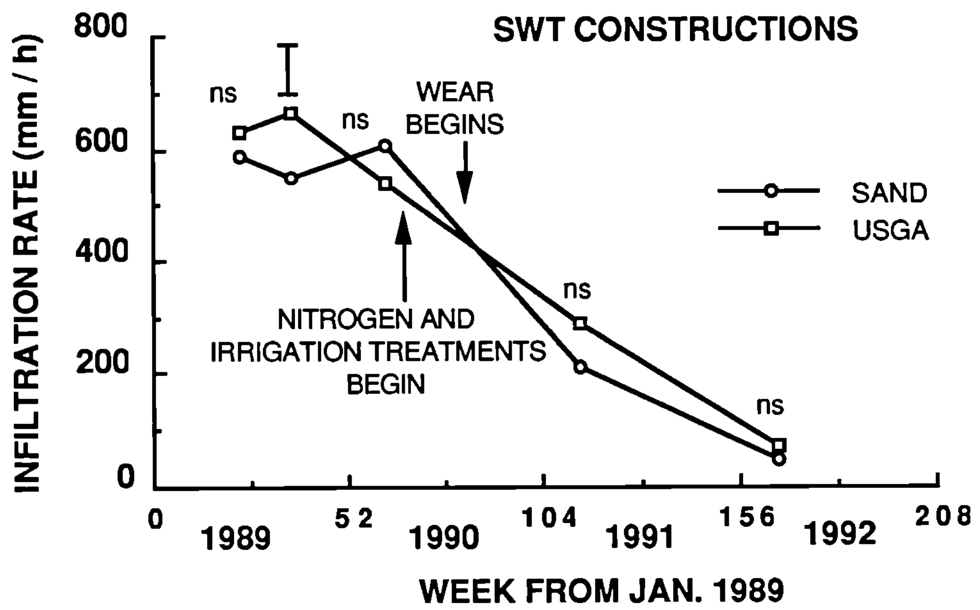

FIGURE 3.8

Infiltration rates (mm hr^{-1}) of the two SWT constructions on 5 occasions during the trial period. Vertical bar represents the LSD ($p \leq 0.05$) for the main effect of construction type. ns denotes non-significant differences.

Figure 3.8 shows the infiltration rates of the sand and USGA constructions on three occasions prior to, and two following, the onset of wear and the irrigation and fertiliser treatment programme. Before wear and differential treatment application, infiltration rates remained around 600 mm h^{-1} for both SWT constructions. That of the USGA construction was significantly greater in week 37 (September) 1989. Afterwards, rates fell to around 40 % of the early values in week 10 (March) 1991, and to around 10 % in week 11 (March) 1992.

The soil construction infiltration rates are shown in Figure 3.9. These remained below 10 mm h^{-1} for the 1990, 1991 and 1992 assessments, but showed a temporary rise to 22 mm h^{-1} in week 37 (September) 1989. This assessment was carried out three weeks after the verti-drain treatment described in Section 2.6 vi.

Infiltration rates on the SWT constructions were significantly greater at the higher rate of nitrogen fertiliser application (410 kg N ha^{-1} yr^{-1}). This phenomenon was not observed on the soil constructions. Changes in infiltration rate on each construction type between March 1990 and March 1992 in response to nitrogen fertiliser rates are shown in Table 3.9.

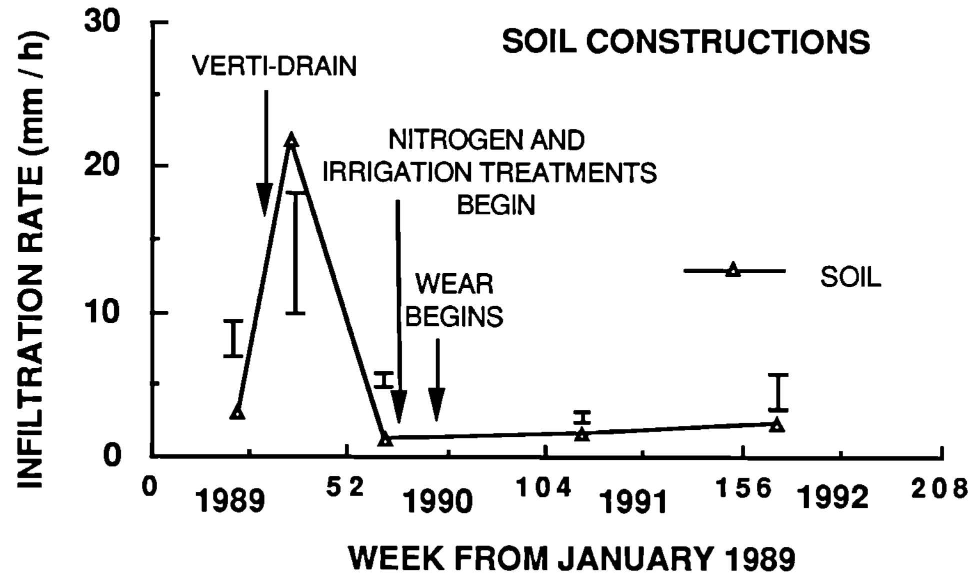

FIGURE 3.9

Infiltration rates (mm hr^{-1}) of soil constructions on 5 occasions during the trial period. Vertical bars represent the standard deviation of the data.

DATE	CONSTRUCTION TYPE						LSD
	SAND		USGA		SOIL		
	N2	N4	N2	N4	N2	N4	($p \leq 0.05$)
March 1990	615	596	545	532	1	2	ns
March 1991	182	245	197	377	1	2	29
March 1992	39	54	56	84	2	3	18

TABLE 3.9

Changes in infiltration rate (mm h^{-1}) on each construction type between March 1990 and March 1992 in response to nitrogen fertiliser rates of 110 kg N ha^{-1} yr^{-1} (N2) and 410 kg N ha^{-1} yr^{-1} (N4). The LSDs refer to comparisons between means of the same construction type, ns denotes such differences which were non - significant.

3.4 DISCUSSION

The high level of rainfall received during the 1992 irrigation treatment period unfortunately reduced the severity of the irrigation treatments quite considerably. This highlights the difficulties of using the automated irrigation control system, which was unable to account for rainfall, and was discussed in Section 2.8. The conditions which prevailed during 1992, in comparison with earlier particularly dry years, did not produce any serious drought symptoms on any fine turf area in the locality of the trial. For future studies investigating turf irrigation in the UK, this would suggest that field trials should be sited in areas such as East Anglia where low rainfall is more certain and irrigation treatments may be more tightly controlled. SMD responses to the irrigation treatments did occur however on all three construction types, and therefore some conclusions may be drawn regarding the nature of the interactions between the three construction types and irrigation.

The definition of field capacity as the amount of water remaining after the saturated lysimeters had drained for 24 hours was largely arbitrary since different soils may continue to drain for many weeks (van Bavel *et al.* 1968). This may have caused discrepancies to occur between the measured field capacities and the "stable state" SMDs of the three construction types. The observed stable state SMD of the lysimeters throughout the wetter periods of the year may have represented the true field capacity more closely, particularly on the suspended water table constructions. Such a discrepancy would be more likely to occur, however, in finer textured soils rather than the comparatively coarse SWT rootzones, and notably did not occur on the soil constructions.

For an SWT construction which is at field capacity, theory suggests that if irrigation is applied at a rate above that required to lower the SMD to field capacity, the excess will be lost. If rainfall plus irrigation is equal to ET then the rootzone will be maintained at field capacity and if the inputs of rainfall and irrigation are less than evapotranspiration the rootzone will dry out.

On the sand construction, the SMD data agreed to some extent with the theory of the suspended water table. The 100% and 140% TDET treatments produced very similar effects on SMD, while SMD for the 60% TDET treatment increased, especially during the drier period from July to mid September. During the course of the measurement period however, all three construction types exhibited moisture deficits which showed the same seasonal pattern as that predicted by MORECS.

In all cases the effect of even the highest rate of irrigation was not able to prevent the development of large, seasonal SMDs. The moisture deficits could have been substantially reduced on several occasions by rainfall alone, even without the more or less constant supply from the irrigation system. This would suggest that either ET losses were generally underestimated, or that water arriving at the surface of the turf was not incorporated into the available space and a good deal by-passed the rootzones either as runoff or drainage or both. Moisture deficits occurring on the USGA construction may have been due to greater drainage losses. The drainage volume data appear to support this hypothesis.

The SWT principle would therefore appear not to function exactly as its designers had intended with respect to water retention. The differential SMDs which developed in response to the differing irrigation treatments must have come about to some extent by differential drainage or runoff losses. This would imply that factors affecting these features, such as rootzone infiltration rate and structure, are of greater significance in affecting plant-available water.

On the soil constructions, both the 140% and the 100% TDET replacement treatments were also inadequate to maintain SMD at a state approaching field capacity. This may have been due to underestimates of ET (and TDET derivation) as discussed above, or may reflect a tendency towards greater water use on this construction type. In general, the turf growing on the soil constructions was of a denser, more lush nature than that grown on the suspended water table constructions (see Chapter 4). Greater water loss by ET may therefore have taken place due to there being a greater surface area of transpiring leaves. Drainage, ET and runoff losses were not measured on the soil constructions. This may indicate an area where further research is necessary.

A possible source of error arising in the measurement of ET_m may have been the estimation of the amount of irrigation water arriving at each lysimeter ("I" in equation 3.8). Other workers (eg Feldhake *et al.*, 1983) applied irrigation water to lysimeters using a graduated cylinder at the time of each weighing, and Feldhake *et al.* (1984), investigating the effects of irrigation on ET, covered each lysimeter in order to prevent sprinkler irrigation water entering them. This experiment was designed to examine only major changes in ET which may have occurred in response to the applied treatments, since this is the first measurement of ET losses from turf mown at 5 mm in the UK. If similar methods are to be used to monitor finer changes in such turfgrass ET, for example inter - specific differences, the method of irrigation application would have to be more precise.

Aronson *et al.* (1987) tested the formulae for deriving $ET_{Aronson}$ against the loss of water from 50 mm turf for which water availability was not limiting. That water availability is not limiting is an essential precept for the application of the Penman formula (Penman 1948, 1963) or its derivatives. The close correspondence of the ET_m measurements with the predicted values of $ET_{Aronson}$ would therefore imply that the SMDs observed in the experiment did not restrict the biological processes involved in the control of ET and that no major differences existed in the rate of ET from 5 mm and 50 mm turf.

The correspondence is however somewhat surprising since the formula for deriving $ET_{Aronson}$ contains no canopy resistance term which is generally considered essential for accurate prediction of actual ET from crops (Kim & Beard 1988). Johns *et al.* (1983) found that the actual values of surface resistance to ET of well watered alfalfa, barley and sugar beets were comparable to those of St Augustine grass (*Stenotaphrum secundatum*) turfs and concluded that ET rate was controlled to a large extent by factors external to the plant rather than by stomatal control. If the same conclusions may be applied to the *Festuca / Agrostis / Poa* swards described here, although experimental error may have shrouded some physiological responses, ET losses were mainly determined by meteorological phenomena and the influences of the construction types or the irrigation treatments on ET were negligible. This highlights the importance of the influence of construction and/or rootzone type on water retention, drainage and runoff in turf management.

The VMC values (in %) of the tension table cylinders could be converted to SMD values (in mm), assuming that the ratio of sample cylinder VMC to cylinder field capacity VMC is the same as that of sample lysimeter moisture content to lysimeter field capacity moisture content. The difficulty is in identifying the appropriate tension to define the moisture content at field capacity. Webster & Beckett (1972) found that the tension in the surface horizons of well - drained, English soils was typically 3 - 7 kPa during winter and spring and therefore proposed that 5 kPa could be used. Other workers have found that higher values are more appropriate. For example, Haise (1955) found that 10 kPa was a suitable value, while Colman (1947) found that values as high as 33 kPa were acceptable.

The range of tensions applied by the sand tension table may therefore reflect little more than the gravitational forces affecting the water content of the three constructions. Considering the mean cylinder VMCs of each construction type on the cylinder sampling date in week 22 (May) 1991, the closest correspondence with the SMDs measured with the lysimeters was achieved by using field capacity tension equivalents of 3.0 kPa, around 2.0 kPa and 7.5 kPa for the sand, USGA and soil constructions respectively. Re-drawing the characteristic moisture release curves of the three constructions using SMDs derived from these field capacity tensions shows that between field capacity and a SMD of 70 mm (approximately the largest measured in 1992 on the SWT constructions), water is held between tensions of 3.0 and 6.0 kPa on the sand, and between 1.5 and 6.0 kPa on the USGA constructions. In contrast, on the soil constructions, the 0 to 9 kPa tension range was not able to reduce SMD to below the equivalent field capacity.

These results imply that the sand tension table is adequate to study moisture release characteristics of pure sand and USGA constructions, but for soil - based media much greater tensions need to be applied to adequately simulate field conditions. Plant roots are able to extract water from soil pores as small as 0.2 μm diameter, corresponding to tensions of 1500 kPa (Payne 1988). Between field capacity and 70 mm SMD, on the SWT constructions, water is lost from pore sizes greater than 50 μm. This indicates that, on the SWT constructions, turfgrass responses to the irrigation treatments (see Chapter 4) may have been brought about by little more than gravitational water loss.

The loss of water by drainage from the SWT constructions, and the USGA construction in particular, when SMDs were high, may reflect the hysteresis effect of re-wetting soils (Poulovassilis 1962). Briefly, this phenomenon means that for a given applied tension, a soil may hold more water during drying than during wetting. This phenomenon would explain why the cylinder weights hardly increased at all as the tension table was returned to 0 kPa water potential. Rewetting dry rootzones may therefore necessitate holding water at lower tensions than those which are finally achieved for periods long enough for equilibration to take place. Since the critical ranges of tension governing the water content of the SWT constructions lie around the gravitational region, then either a constant through-flow of water, or "backfilling" by blocking drainage outlets and applying irrigation, until equilibrium is achieved may provide methods of returning depleted rootzones to field capacity.

The soil construction infiltration rates were unacceptably low (Baker & Richards 1993) for virtually the entire duration of the trial, with the brief exception of the period immediately following the verti-drain treatment. The mean output rate of the sprinklers (24.3 mm - see Section 2.7) did not exceed the lowest infiltration rate on the SWT constructions and so virtually all irrigation water arriving on these constructions may be assumed to have penetrated the turf surface. On the soil constructions, however, the low infiltration rates meant that an appreciable proportion of both rainfall and irrigation must have flowed off the plots.

The main structural differences between the SWT rootzones and the soil construction lay not as major variations in total porosity, but as differences in moisture release characteristics or pore size distribution. The infiltration of surface water, as measured in this study, is largely a mass flow process taking place under the influence of gravity. The vast differences in infiltration rates between the soil and the SWT constructions may therefore reflect variation in the proportions of pore spaces of sizes subject to gravitational water loss. For example, pores greater than about 67 μm diameter (ie. equivalent to moisture potentials of less than -4.5 kPa) comprised 63 % of the total pore space of the SWT constructions, but only 7 % of that of the soil constructions. This may account, to some extent, for the differences in infiltration rates.

The soil physical performance of the USGA mix and pure sand rootzones were, in essence, very similar, especially when compared with the soil rootzone. Both the SWT rootzones had infiltration rates above 20 mm h^{-1}. Although the relationship between particle size and pore size distribution in soils is a complex one, it is likely that the slightly coarser sand grains of the USGA rootzone (Section 2.4) compared with those of the sand will have given rise to the slightly larger proportion of total pore space of diameter greater than 100 μm and the differences in the movement and retention of water.

A striking feature of the infiltration rate data was the decline which took place on the SWT constructions following the onset of wear. This took place despite the fact that structural features of these rootzones showed little corresponding variation. This agrees with the observations of Schmidt (1980), who found that, after eight years of wear treatment, both air porosity and infiltration decreased, but air porosity reduction was less than the decrease in water infiltration. Schmidt suggested that, with time, the shifting of the mix of particles impeded water movement by increasing tortuosity rather than by reducing total pore space. In effect, water infiltration may have been limited by the sealing of the surface. The wear treatment applied in this study may therefore have limited the infiltration of water on the SWT constructions by this means, rather than compaction of deeper layers of the rootzone.

On the soil constructions however, some structural changes did take place, namely a 7 percentage points reduction in the total pore space greater than 67 μm diameter. Had the infiltration rates been generally greater, this phenomenon may have induced a general decline in infiltration rates over the wear period.

The capping of the SWT constructions is likely to have come about through the build up of organic matter from dead leaves or other organisms such as algae which were observed in the turf. This would indicate that scarification procedures are of some considerable importance in the maintenance of satisfactory infiltration rates on sand - based rootzone media.

On the soil constructions, the short-lived effects of the verti-drain treatment may have been due to the collapse of the holes over the winter of 1989 / 1990. This would suggest that the procedure should be employed on a regular basis for its advantages to be maintained. It was noted at the time of carrying out the verti-drain operation that considerably greater quantities of sand could have been applied. Given the importance of the proportion of larger pore spaces through which water may flow under gravity in a golf green, it is likely that the effectiveness of the verti-drain treatment may be enhanced and prolonged by the application of liberal quantities of a uniform, coarser, material (sand) following treatment.

CHAPTER 4 - ECOLOGICAL PROCESSES

4.1 INTRODUCTION

A better understanding of the ecological processes occurring in golf greens should help the greenkeeper to target management practices more accurately towards improving turf quality. A first step towards this goal is to consider the dynamics of species composition which may take place in greens in response to the treatment factors imposed. Each treatment combination may, in time, produce a characteristic and more or less stable community. Each community may then remain in a state of equilibrium, provided the management factors associated with it are kept constant. The time delay between the sowing of the bare seed-bed and the development of the equilibrium condition of the turf may vary, depending on the consequences for the plants of the particular treatment combinations, but a description of its community at any point between these two periods would represent a momentary state during a directional change in condition.

This approach is analagous to the classical concept of vegetational succession and climax originated by Warming (1896) and developed by Clements (1916). These workers considered only natural vegetation and their ideas have been subject to numerous criticisms. For example, the concept of vegetational stability demands a reference to a time scale and, for many natural populations this scale exceeds that of the lifespan of man. Over such a time scale other factors, such as climate, which may influence the process of succession, may change. Climax vegetation is therefore an abstract concept. Over the relatively short duration of the trial however, observed changes in sward composition may be considered as successional changes, the course of which are influenced by the treatment factors imposed. It may therefore be possible that the results obtained over the trial period could be extrapolated to predict the eventual outcome of the treatments over longer periods more representative of the lifespan of an actual golf green.

The measurement of species performance in a golf green is to some extent made easier by the fact that the height of the above ground community is so low. This means that vertical stratification is minimal (though by no means non-existent) and the community can effectively be considered two dimensional. An informative estimate of turfgrass performance would therefore be that of percentage ground cover occupied by the overall set of grasses, and the proportional contributions of individual species to this. Ground cover is usually measured using a point quadrat. The principles of cover assessment have been thoroughly and critically discussed by Goodall (1952). For the applications of these methods to close mown turf a number of considerations call for comment. The diameter of pins used in point quadrats may greatly affect the estimate of cover obtained, the larger the diameter the greater the estimate (Goodall 1952). This phenomenon is of major importance in fine turf situations where the size of the plants being measured are small. To approximate more closely to an infinitesimally small point, the optical point quadrat was developed (Laycock and Canaway 1980). With this, points are obtained using pairs of pins held horizontally one above the other such that the tips may be aligned by eye to define a very small point on the ground below. Hits or misses at each point are then recorded.

Another method of measuring species performance in close-mown turf is to examine shoot density. For the species under consideration, in established turf, individual whole plants cannot readily be recognised, but individual tillers are relatively easily distinguished. The generally high densities, and small plant sizes, means that measurement procedures are rather time consuming which explains the dearth of literature on tiller density of mixed species, fine turf. Tiller density is of interest because, for a given level of total ground cover, it provides an indication of average plant size. This may reflect general features of the turf such as perceived visual quality and wear tolerance, thus providing a standard method of assessing the relative performance of golf greens with respect to these features. This is considered further in Chapter 6. Tiller density, in conjunction with ground cover measurements, may also be used to indicate morphological changes which may take place in turfgrass species in response to the treatment factors imposed and the environments subsequently created.

The particular species composition and growth forms of the swards of golf greens arise in response to interactions between a massive range of climatic, seasonal, edaphic, biotic, genetic and managerial factors. Effects observed in response to the treatments carried out in this study must therefore be considered in this wider context. For example, the perceived main effects of construction type on sward composition may have come about through its influence on the relative rate of germination from the original sowing mixture (Section 2.6), on the relative rate of development of incoming propagules of species other than those sown, on the relative rate and form of growth and development of established individuals, and on the nature of any interference which may take place between the species eventually present. The identification of the exact means by which treatment factors bring about changes in sward composition is therefore extremely difficult.

Ecological studies are frequently performed which aim at relating particular edaphic features with plant growth responses and establishing a degree of causality between the two. The treatment factors imposed in this project brought about changes in sward composition chiefly through events taking place in the rootzone media. Physical distinctions, such as water relations and soil structure and texture, came about largely through the construction and irrigation treatments and were described in Chapter 3. Edaphic factors pertaining to the nutritional effects on the swards would have been influenced to a much greater extent by the interactions of these features with the nitrogen and phosphate fertiliser treatments imposed. Thus, phosphate fertiliser treatment effects may be a more direct function of the actual levels of available phosphate created in the rootzone, as influenced by factors such as its pH and organic matter content, in addition to the rootzone physical features and the rate of fertiliser application. Measurements of the rootzone phosphate levels, pH and organic matter content may therefore help to illuminate any causal relationships with the observed sward characteristics.

The measurement of plant - available soil phosphate is complicated by the fact that the ion is partitioned between an inorganic matrix, mineral surfaces, organic matter and the soil solution. The concentrations in the soil solution are extremely low (Wild 1988b) and "surface" phosphate, which is probably the most relevant factor, may only be defined by the method of its determination. However, provided care is taken to use standard procedures for its measurement, it may be posssible for comparisons between soils to be made with some degree of confidence.

The solubility of fertiliser nitrogen applied to golf greens, and the consequent mobility of the nutrient, means that the nitrogen levels in the rootzone are extremely variable. For this reason, measurements of rootzone nitrogen levels of fertilised turf at any one time are of limited value and cannot be meaningfully compared over time. The macro-nutrients potassium and calcium are however readily measureable and, although fertilser applications of these elements were not incorporated into the treatment programme of the trial, their levels in the rootzones may have been a function of some treatment factors or their effects and have subsequently influenced the recorded sward characteristics.

In this chapter, above ground characteristics of the plant communities arising in response to the treatment factors imposed are described in terms of; (i) the changes in ground cover after three years of differential treatment, (ii) the progress of these changes over the trial period, and (iii) the tiller density at the end of the trial period. These data are examined alongside measurements of rootzone pH, phosphate, potassium, calcium and organic matter content in an attempt to generate hypotheses and general statements pertaining to the relationships between construction or rootzone type, fertiliser and irrigation management and the botanical nature of golf greens.

4.2 MATERIALS AND METHODS

Ground cover

Cover and botanical composition were assessed in week 27 (July) 1989, weeks 12 - 13 (March) and 39 - 40 (September - October) 1990, weeks 11 - 12 (March) and 39 - 40 (September - October) 1991, and weeks 13 (March) and 39 - 41 (September - October) 1992 using an optical point quadrat frame (Laycock and Canaway 1980). Five pairs of pins were used in the frame, each pair separated by 10 cm. The frame was placed systematically 20 times on each sub-sub-plot such that the whole 2 x 2 m area was examined and 100 points were obtained in each case. In addition to the living, sown species (*Festuca rubra* and *Agrostis* spp.), *Poa annua* cover was recorded. Dead material was defined as grass which was no longer green, and bare ground as hits directly onto the rootzone material. Prostrate, semi-decayed organic material was defined as litter. Bryophytes and other plant species were identified and recorded when hit.

Shoot density

Shoot density was measured between September and November 1992 in order to correspond with the ground cover assessment of weeks 39 - 41 (September - October) of that year. Counts were made of the numbers of shoots of *Agrostis* spp., *P. annua* and *F. rubra* in each of nine cores taken from each sub-sub-plot. The cores were taken from systematically arranged points corresponding to the corners, centre and side-mid-points of an hypothetical square of side 1.3 m placed in the centre of each sub-sub-plot. The corer used was a hollow tine core with an internal diameter of 10 mm.

Although every effort was made to ensure that all treatments were applied evenly to each sub-sub-plot, heterogeneity in shoot density within individual sub-sub-plots was frequently apparent. This was evident as the patchy occurrence of individual species within the living sward and of the whole sward itself. For the shoot density measurements, within sub-sub-plot variability due to this patchiness was often likely to have been large because, in essence, only 9 observations were made in each case. By dividing the shoot density values by the corresponding proportion of total live cover (TLC - measured with the point quadrat and therefore based on 100 observations), estimates of the shoot density of the grass actually present were obtained. This transformation was of greatest significance when total live cover was substantially less than 100 %. One advantage was that the inverse of cover adjusted shoot density could provide an indication of the "size" of individual shoots.

Rootzone pH, P, K, Ca and organic matter content

Rootzone samples, consisting of approximately 500 g formed from 25 sub-samples, were taken from each sub-sub-plot to a depth of 100 mm in weeks 11 (March and 42 (October) of 1990, 1991 and 1992. (The October 1992 data had not been analysed at the time of writing and hence is not described in the following section). Each sample was air dried, broken up and passed through a 2 mm sieve prior to analysis. P and K were extracted with 0.5 M acetic acid. Flame photometry was used to determine K, and P was measured by the method of Murphy & Riley (1962) which estimated the total amount of labile phosphate extracted from the sample. The calcium content of the samples collected in March 1991 was extracted with 1 M ammonium nitrate and measured by the method described by Gough (1973) for the estimation of magnesium. Calcium content of the extract was measured with an atomic absorption spectrophotometer (Instrumentation Laboratory 357). The pH of the samples was determined by adding 25 ml distilled water to 20 ml of sample. After stirring, the mixture was allowed to stand for 1 hour at 20 °C and then pH was measured by a combined glass-reference electrode inserted into the sample/water mixture. The organic matter content of the samples collected in March 1992 was measured by the loss in weight after ignition in a muffle furnace at 400 °C for 8 hours.

4.3 RESULTS

Initial botanical status

The percentage cover of the sown species, (*Agrostis* spp., *F. rubra*) on each construction type in week 12 (March) 1990, immediately before differential irrigation and fertiliser treatments were started are shown in Table 4.1. The soil construction supported the highest cover of *Agrostis* spp. whilst the USGA and sand constructions showed successively lower amounts of this species. *F. rubra* was most abundant on the suspended water table constructions (sand and USGA) and least so on the soil. At this time there was a 1% cover of *P. annua* on the soil constructions and none on either the sand or USGA constructions. Ground not covered by grass species consisted, at this stage, generally of the respective rootzone media.

Main effects of construction and irrigation

Ground cover

Over the five assessments of ground cover and botanical composition, the main effect irrigation treatment, and the irrigation interaction with the construction treatments, produced no significant changes in total live cover (TLC), or in the contributions to this of *F. rubra* and the weed species *Poa annua* L.

	SAND	USGA	SOIL	LSD ($p \leq 0.05$)
Agrostis spp.	21	35	83	8.6
F. rubra	52	46	11	8.7
Total	73	81	94	-

TABLE 4.1.
Percentage cover of sown species in week 11 (March) 1990, prior to differential irrigation and fertiliser treatment.

The presentation of changes in botanical composition over the course of the trial period is of course dependent on the particular interactive combinations of treatments under consideration (see Section 2.2). In order to provide a general overview of botanical composition changes on the three construction types, however, the mean cover of *Agrostis* spp., *F. rubra* and *P. annua* and, by summation, the total cover provided by all these species (TLC) on the sand, USGA and soil constructions are shown in Figure 4.1.

On the sand constructions, the mean TLC showed an overall decline over the treatment period. This decline took place chiefly at the expense of *F. rubra*. Cover of *Agrostis* spp. generally increased over the treatment period and *P. annua* cover remained relatively low. On the USGA constructions, *P. annua* remained virtually absent throughout the trial period and *Agrostis* spp. increased markedly as *F. rubra* declined. Mean TLC remained relatively constant. On the soil constructions, the initially low cover of *F. rubra* continued to decline over the treatment period, as did that of *Agrostis* spp. However, the cover of *P. annua* increased while the TLC remained relatively constant. Each construction showed a general, temporary decline in ground cover of all species in week 11 (March) 1991.

Shoot density

The main effects of the irrigation treatment had no effect on the mean total shoot density (sum of *Agrostis* spp., *F. rubra* and *P. annua* counts) across each construction type, measured in October 1992. Values were 41.9, 65.8 and 93.4 thousand shoots m^{-2} (LSD [$p \leq 0.05$] = 7.2) on the sand, USGA and soil constructions respectively.

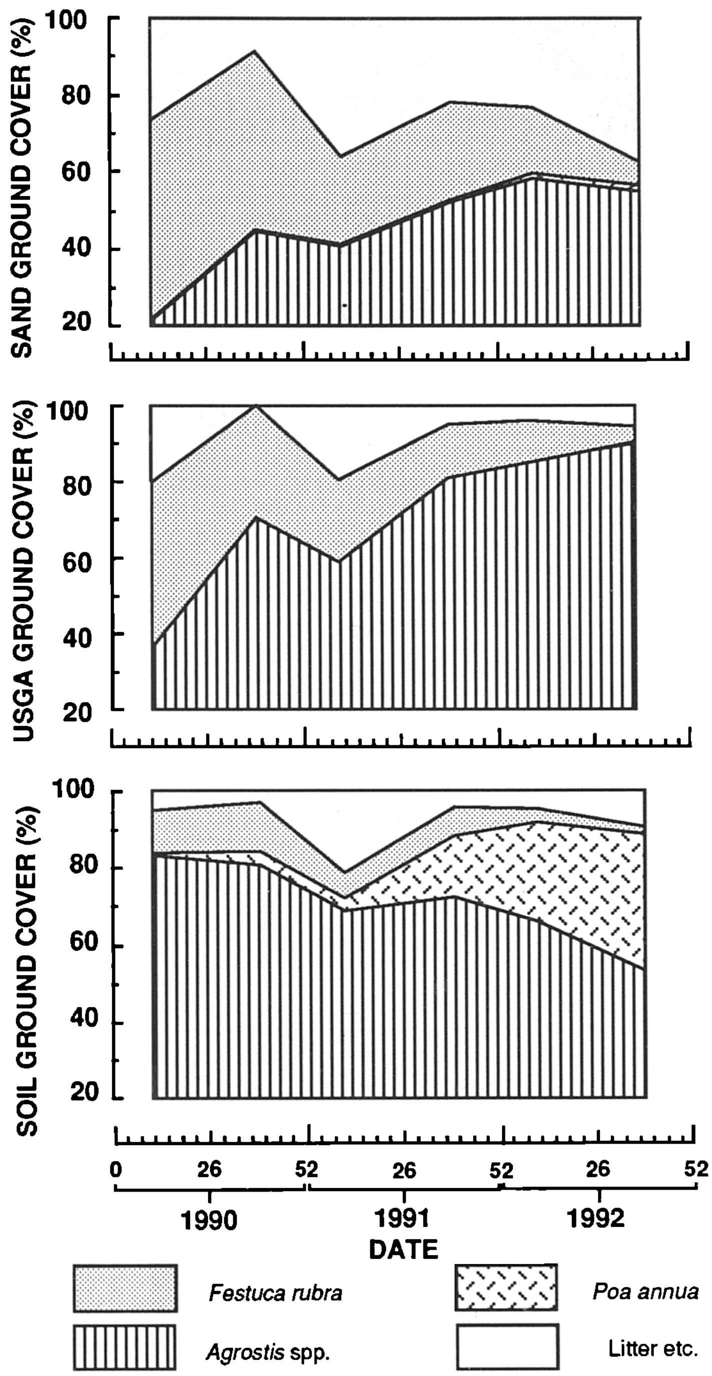

FIGURE 4.1

Changes in mean cover of *Agrostis* spp., *P. annua*, *F. rubra* and litter etc. on the sand (top), USGA (middle) and soil (bottom) construction types between week 11 (March) 1990 and week 42 (October) 1992.

Mean, cover-adjusted, shoot density values for the three construction types were 63.8, 88.9 and 103.9 thousand shoots m^{-2} respectively (LSD [$p \leq 0.05$] = 6.0). The shoot density of *Agrostis* spp., adjusted for the relative cover of the species, was significantly affected by the construction type. Values were 67.4 on the sand, 93.9 on the USGA and 132.4 thousand shoots m^{-2} on the soil constructions (LSD [$p \leq 0.05$] = 28.8). The shoot density of *P. annua*, adjusted for the relative cover of the species on the sand was 10.8, on the USGA was 35.0 and on the soil constructions was 80.4 thousand shoots m^{-2} (LSD [$p \leq 0.05$] = 29.3).

Rootzone analyses

The mean rootzone pH and phosphate content of the three construction types was unaffected by the main irrigation treatment throughout the trial period. The pH values of the rootzone media in week 11 (March) 1990, immediately prior to the application of differential fertiliser and irrigation treatments, were 5.0, 4.5 and 6.1 (LSD [$p \leq 0.05$] = 0.16) for the sand, USGA and soil constructions respectively.

The mean phosphate contents of the three rootzone media showed a continual general decline over the course of the trial period. These data are shown in Figure 4.2. The soil constructions consistently showed the greatest phosphate content and the USGA constructions showed the least. From initial levels of 19.6, 15.9 and 23.9 mg l^{-1} of air dried rootzone media for the sand, USGA and soil constructions, phosphate content fell to the levels recorded in March 1992 by 43, 48 and 53% respectively. Both rootzone pH and phosphate content were greatly affected by the fertiliser treatments.

Rootzone calcium content measured in March 1991 showed no significant response to irrigation treatments, but was significantly different ($p \leq 0.001$) among construction types. Calcium concentrations were 0.4, 1.2 and 16.7 mg l^{-1} on the sand, USGA and soil constructions respectively (LSD [$p \leq 0.05$] = 1.6). Organic matter content measured in March 1992, also showed no significant response to irrigation treatments, but was significantly different ($p \leq 0.001$) among construction types. Organic matter contents were 0.5, 1.3 and 3.8 % on the sand, USGA and soil constructions respectively (LSD [$p \leq 0.05$] = 1.6).

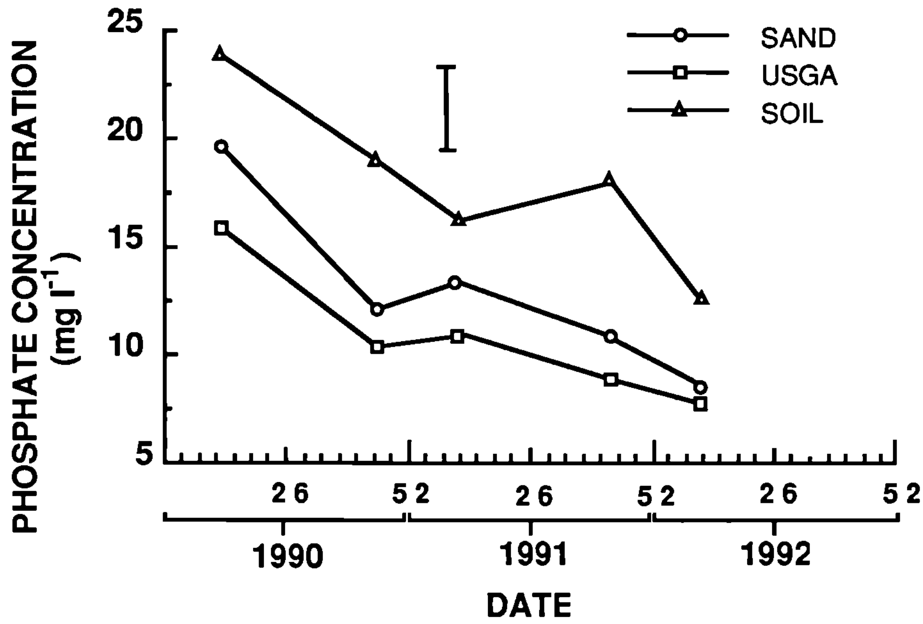

FIGURE 4.2

Changes in rootzone phosphate concentration (0.5 M acetic acid extract) on the sand, USGA and soil construction types between week 11 (March) 1990 and week 11 (March) 1992. The vertical bar represents LSD ($p \leq 0.05$) for all possible pairs of means presented.

In contrast to the results for calcium and organic matter, the potassium content of the respective rootzone media was affected by the differential irrigation rates. These data, collected in week 41 (October) 1991, are shown in Table 4.2. Rootzone potassium content showed a significant decline on the SWT constructions with increasing rate of irrigation. On the soil constructions this relationship was not so clearly defined, although potassium content at 140 % TDET was significantly lower than that at 100 % TDET. The effects of increasing irrigation in lowering potassium concentration first became significant on the sand constructions in October 1990 and on the USGA constructions in October 1991.

Time trends for rootzone potassium content are shown in Figure 4.3. The mean potassium content of all three rootzone media increased between the March and October measurements in 1990 and 1991 and decreased in the winters of 1990/91 and 1991/92. The greatest fluctuation took place between March 1991 and 1992. From initial levels in March 1990, which did not differ significantly between construction types, the highest mean rootzone potassium content in March 1992 was recorded on the soil constructions and the lowest was on the sand constructions, although the overall mean was not significantly different from the initial value.

IRRIGATION RATE	SAND	USGA	SOIL
60% TDET	62	83	64
100% TDET	46	51	72
140% TDET	37	48	53
MEAN	48	61	63

TABLE 4.2

Main effects of irrigation on rootzone potassium concentration (mg l^{-1} of rootzone media) on each of the three construction types in October 1991. LSDs ($p \leq 0.05$) were 6.8 for comparisons between means of the same construction type, 11.5 for all comparisons in the construction x irrigation interaction and 3.6 for the main effect of construction.

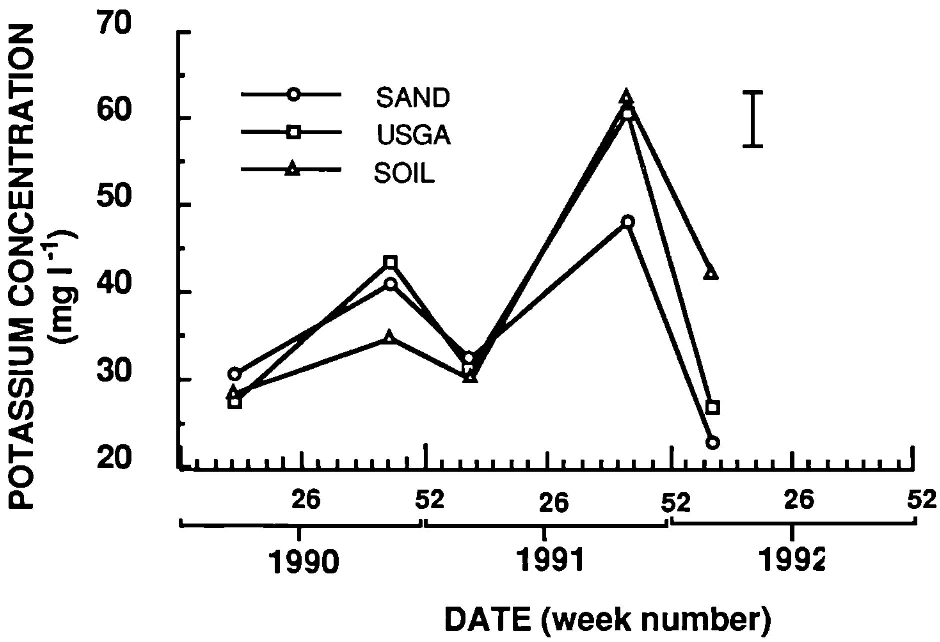

FIGURE 4.3

Changes in rootzone potassium concentration (0.5 M acetic acid extract) on the sand, USGA and soil construction types between week 11 (March) 1990 and week 11 (March) 1992. Vertical bar represents LSD ($p \leq 0.05$) for all possible pairs of means presented.

Interactions with fertiliser treatments

Total live cover (TLC)

Most of the variation among the trial plots came about in response to the interactions of the construction types with both the fertiliser and the irrigation treatments. The TLC on the three construction types in week 42 (October) 1992 in response to three seasons of treatment with five rates of nitrogen, with and without the phosphate fertiliser treatment, are shown in Figure 4.4. On the SWT constructions treated with phosphate fertiliser, TLC increased with increasing rate of nitrogen application to maximum values of 95% on the sand constructions at rates of both 235 and 410 kg N ha^{-1} yr^{-1}, and 98% on the USGA constructions at a rate of 410 kg N ha^{-1} yr^{-1}. Above these rates live ground cover showed a marked decline. The USGA construction sub-plots not treated with phosphate fertiliser reached a maximum of 85% cover at 235 kg N ha^{-1} yr^{-1}, but maintained a lower cover at all rates of nitrogen. Sand construction sub-sub-plots not treated with phosphate fertiliser showed no significant response to nitrogen fertiliser and showed a mean total live ground cover of 48%. On the soil constructions the application of phosphate fertiliser had no significant effect on total live ground cover. Mean values increased with increasing nitrogen from 76% at the lowest rate to between 96 and 98% at rates of 235 to 635 kg N ha^{-1} yr^{-1}.

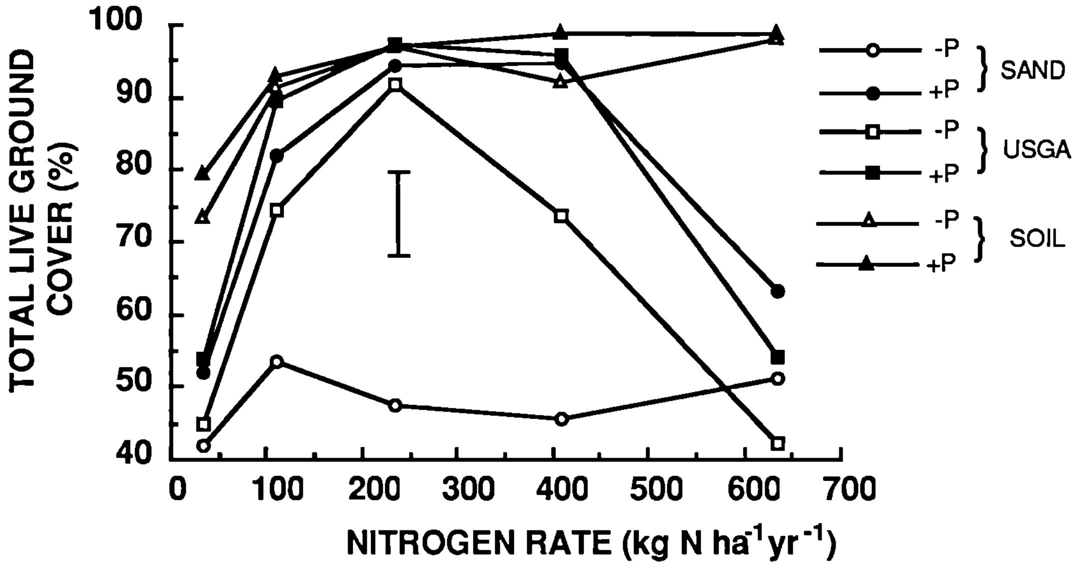

FIGURE 4.4

The effects of 5 rates of nitrogen fertiliser with and without phosphate fertiliser on the percentage TLC on the three construction types in week 41 (October) 1992. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

A significant interaction took place between the irrigation, construction and nitrogen fertiliser treatments with respect to TLC. On the SWT constructions, at the highest rate of application of nitrogen fertiliser (635 kg N ha^{-1} yr^{-1}), the lowest rate of irrigation (60% TDET) produced a reduction in TLC which did not occur at the higher irrigation rates. This effect was greatest on the USGA constructions, and was only apparent at the 635 kg N ha^{-1} yr^{-1} fertiliser rate. This TLC data from week 41 (October) 1992 is shown in Table

4.3. The effect was not detected at all on the soil constructions and occurred, for the most part, during the growing season of 1991.

IRRIGATION RATE	SAND	USGA	SOIL
60% TDET	41	13	99
100% TDET	67	60	99
140% TDET	65	72	98

TABLE 4.3
The effects of three rates of irrigation on total live cover on each of the three construction types receiving the highest rate (635 kg N ha^{-1} yr^{-1}) of nitrogen fertiliser application in week 42 (October) 1992 (%). The LSD ($p \leq 0.05$) for all possible pairs of means presented was 16.3

Percentage of individual species comprising TLC

Having described the responses of TLC to the treatments applied, the proportional contribution of *Agrostis* spp., *F. rubra* and *P. annua* to this feature may be examined. This approach helps to distinguish treatment effects on TLC from effects differentially taking place on individual species.

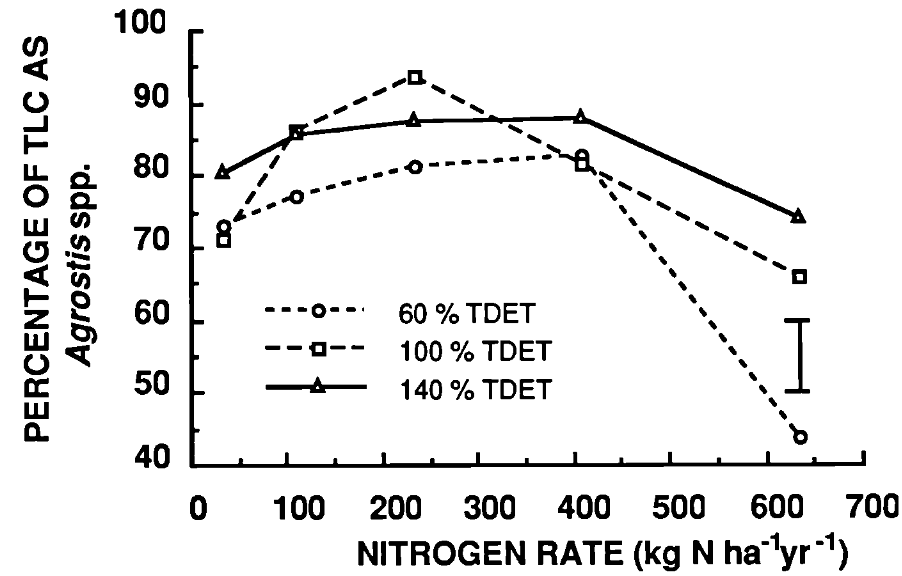

FIGURE 4.5
The effects of 5 rates of nitrogen fertiliser application and three of irrigation on the percentage of TLC occupied by *Agrostis* spp. in week 41 (October) 1992. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

The percentage of TLC across all three construction types in week 41 (October) 1992 contributed by *Agrostis* spp. in response to the nitrogen fertiliser treatments, at the three rates of irrigation are shown in Figure 4.5. For all rates of irrigation, the general response to increasing nitrogen rate was to show an initial rise in the proportion of TLC of *Agrostis* spp., followed by a fall as the highest rates of nitrogen were approached. Maximum values in all three cases lay between 235 and 410 kg N ha^{-1} yr^{-1}. The response was shallowest at the highest rate of irrigation and most marked at the lowest rate. At the highest rate of nitrogen the percentage of TLC of *Agrostis* spp. had fallen to 44% at 60% TDET irrigation rate, whilst at 140% TDET cover only fell to 74%. A similar set of responses was observed in the week 11 (April) 1992 assessment.

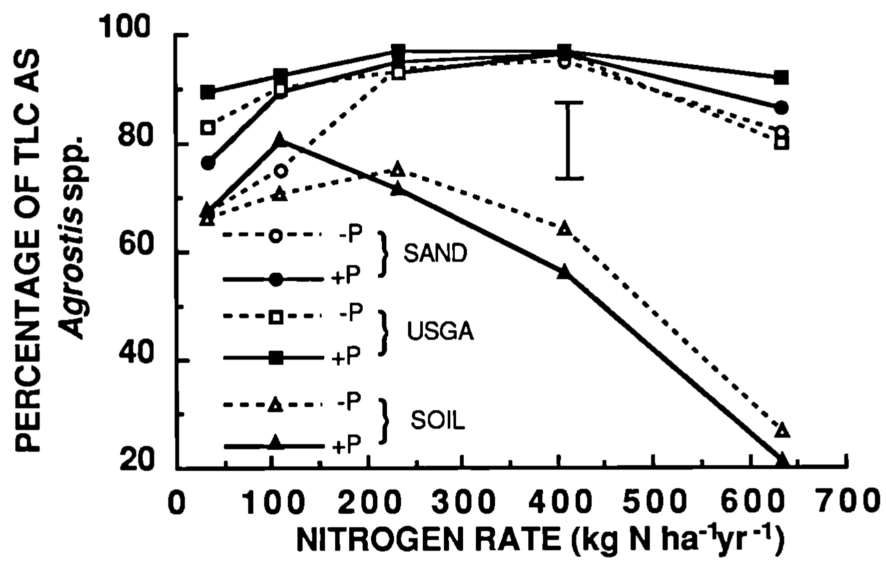

FIGURE 4.6

The effects of 5 rates of nitrogen fertiliser application with and without phosphate fertiliser on the percentage of TLC occupied by *Agrostis* spp. on each of the three construction types in week 41 (October) 1992. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

The percentage of TLC in week 41 (October) 1992 contributed by *Agrostis* spp. in response to the nitrogen and phosphate fertiliser treatments on each of the three construction types is shown in Figure 4.6. On the SWT constructions the proportional contribution increased by 24 % from 72% on the sand constructions and by 9% from 86% on the USGA constructions, as nitrogen rates increased to 410 kg N ha^{-1} yr^{-1}. At the highest rate of nitrogen the percentages on the SWT constructions fell. On the soil constructions the percentages showed an initial rise to 76% as nitrogen rates increased to 110 kg N ha^{-1} yr^{-1}, but thereafter showed a marked decline to 24% at the highest rate of nitrogen fertiliser application. On the SWT constructions the percentage of TLC as *Agrostis* spp. was greater on those sub-sub-plots treated with phosphate fertiliser. This effect was greatest on the sand constructions and was not significant on the soil constructions.

The percentage of TLC in week 41 (October) 1992 occupied by *F. rubra* fell on all three construction types with increasing rate of nitrogen fertiliser. The effects of the nitrogen and phosphate fertiliser treatment are shown in Figure 4.7. The highest proportion of *F. rubra* (25% of TLC on the sand, 11% on the USGA and 4% on the soil constructions) was found on the sub-sub-plots receiving the lowest rate of nitrogen fertiliser (35 kg N ha^{-1} yr^{-1}). As the rate of nitrogen application increased the proportional contributions fell rapidly, reaching 6, 5 and 2% on the respective construction types at a nitrogen fertiliser rate of 235 kg N ha^{-1} yr^{-1}. Phosphate fertiliser application reduced the percentage contribution of *F. rubra* to TLC, most notably at the lower rates of nitrogen fertiliser application. Fertiliser nitrogen had no significant effect on the proportion of TLC on the soil constructions occupied by *F. rubra.*

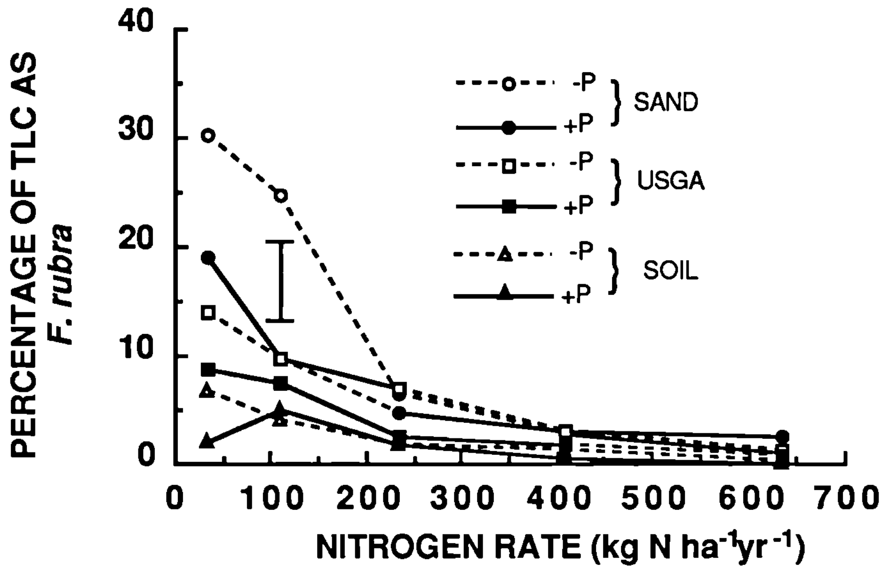

FIGURE 4.7

The effects of 5 rates of nitrogen fertiliser application with and without phosphate fertiliser on the percentage of TLC occupied by *F. rubra* on each of the three construction types in week 41 (October) 1992. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

Over the treatment period the percentage TLC as *F. rubra* declined on all three constructions. The rate of this decline was enhanced on the SWT constructions by higher rates of application of nitrogen. A similar, although less pronounced effect, was observed on the sand constructions in response to the phosphate treatment. Sand construction sub-sub-plots which received phosphate fertiliser showed consistently lower proportions of *F. rubra* .

The effects of nitrogen and phosphate fertiliser treatment on the percentage of TLC in week 41 (October) 1992 of *P. annua* on the three construction types, is shown in Figure 4.8. The proportion was considerably greater on the soil construction, on which it increased with increasing nitrogen application to a maximum of 76% of TLC at the highest rate (635 kg N ha^{-1} yr^{-1}). On the SWT constructions the percentage contribution of *P. annua* also increased at this rate of nitrogen. The phosphate fertiliser treatment had no significant effect on *P. annua* cover.

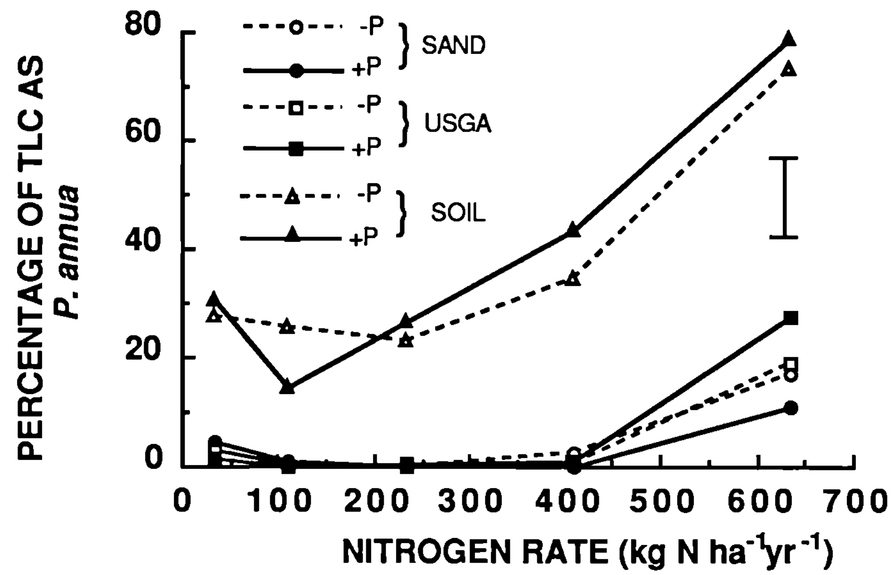

FIGURE 4.8

The effects of 5 rates of nitrogen fertiliser application with and without phosphate fertiliser on the percentage of TLC occupied by *P. annua* on each of the three construction types in week 41 (October) 1992. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

At rates of nitrogen up to 410 kg N ha^{-1} yr^{-1} the proportional contribution to TLC in week 41 (October) 1992 of *P. annua* at all three rates of irrigation, did not significantly differ and had a mean value of 10%. At the highest rate of nitrogen fertiliser application this rose to 55% at an irrigation rate of 60% TDET, 33% at 100% TDET and 25% at 140% TDET (LSD [$p \leq 0.05$] = 11.4).

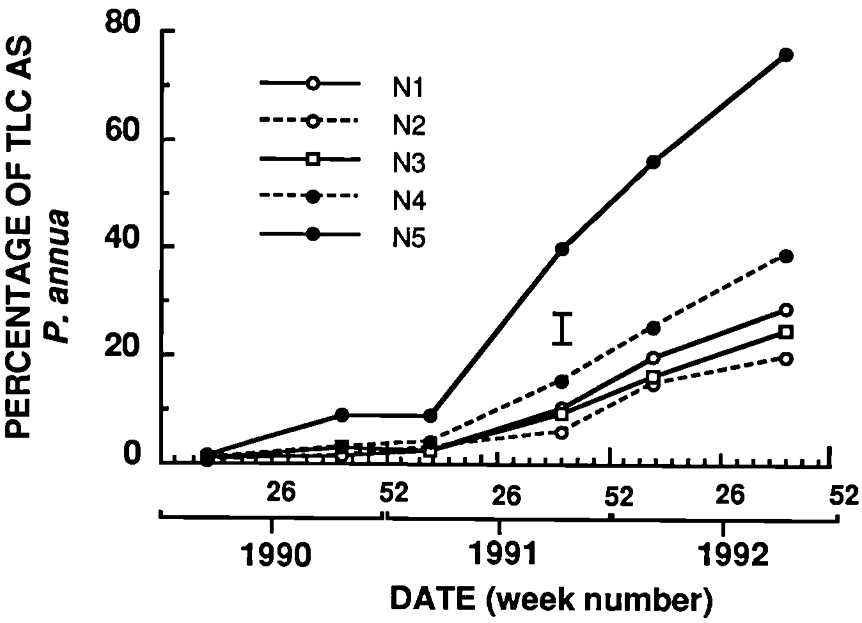

FIGURE 4.9

Changes in percentage of TLC of *P. annua* in response to 5 rates of nitrogen fertiliser application (N1 - N5) on the soil construction type between week 11 (March) 1990 and week 42 (October) 1992. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

The development over the treatment period of the nitrogen response of percentage TLC as *P. annua* on the soil constructions is shown in Figure 4.9. These data show that from March 1991 the 410 and 635 kg N ha^{-1} yr^{-1} rates gave successively higher cover of *P. annua,* in comparison with the lower rates of nitrogen fertiliser application.

The most common weed species, in addition to *P. annua*, was *Sagina procumbens* (Ard.) (pearlwort) in week 41 (October) 1992. This occurred almost exclusively on the soil constructions and was most abundant (between 1 and 2% cover) on those plots receiving the lower rates of nitrogen fertiliser. Two species of moss were recorded on the trial. These were *Eurhynchium praelongum* (Hedw.) and *Brachythecium rutabulum* (Hedw.). The largest amounts of cover of each of these mosses, 8 and 3% respectively, were recorded on the soil construction sub-sub-plots receiving the lowest rate of nitrogen fertiliser (35 kg N ha^{-1} yr^{-1}). *E. praelongum* was found to be most abundant on the soil plots receiving the highest rate of irrigation (140% TDET). Ground cover not occupied by moss or the three grass species was almost invariably occupied by litter which consisted of the dead leaves of the grasses in varying degrees of decay.

Shoot density

The total shoot density increased significantly ($p \leq 0.001$) with the application of phosphate fertiliser on the sand and USGA constuctions. These data are shown in Table 4.4.

CONSTRUCTION TYPE	PHOSPHATE TREATMENT 0 kg P_2O_5 ha^{-1} yr^{-1}	50 kg P_2O_5 ha^{-1} yr^{-1}
SAND	28.0	55.8
USGA	50.3	81.3
SOIL	93.1	96.4

TABLE 4.4
Main effects of phosphate fertiliser on total shoot density (shoots m^{-2}/1000) on each of the three construction types in October 1992. The LSD ($p \leq 0.05$) was 9.6 for comparisons between means of the same construction type and 10.9 for all possible comparisons of the means presented

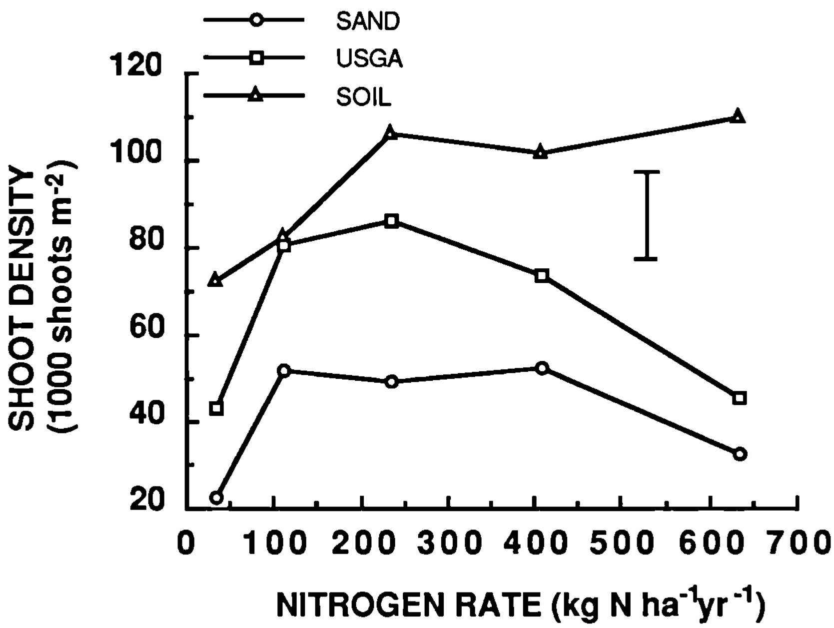

FIGURE 4.10
The effects of 5 rates of nitrogen fertiliser application on total shoot density on the sand, USGA and soil construction types in October 1992. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

The effects of nitrogen on shoot density are shown in Figure 4.10. Total shoot density increased with increasing rate of nitrogen fertiliser on the soil constructions. On the SWT constructions the general response to increasing nitrogen rate was to show an initial rise in total shoot density, reaching a maximum between 200 and 300 kg N ha^{-1} yr^{-1} and falling back as the higher rates of nitrogen were approached. Total shoot density was consistently greatest on the soil constructions and least on the sand constructions.

The effects of phosphate fertiliser on cover-adjusted shoot density on each of the three construction types are shown in Table 4.5. Cover-adjusted shoot density was greatest on the soil and least on the sand constructions. Phosphate fertiliser treatment significantly increased ($p \leq 0.05$) cover-adjusted shoot density, a response which was greatest on the USGA constructions, but not apparent on the soil constructions.

CONSTRUCTION TYPE	PHOSPHATE TREATMENT 0 kg P_2O_5 ha^{-1} yr^{-1}	50 kg P_2O_5 ha^{-1} yr^{-1}	MEAN
SAND	58.3	68.9	63.6
USGA	78.0	99.6	88.9
SOIL	104.5	103.3	103.9
MEAN	80.3	90.6	

TABLE 4.5

Main effects of phosphate fertiliser application on cover-adjusted, total shoot density (shoots m^{-2}/1000) on each of the three construction types in October 1992. LSDs ($p \leq 0.05$) were 15.1 for comparisons between means of the same construction type, 12.3 for the construction x phosphate fertiliser interaction and 8.7 and 6.0 for the main effects of phosphate and construction type respectively

Rootzone pH, phosphate and potassium content

The effects of the five rates of nitrogen and two of phosphate fertiliser on rootzone pH in week 41 (October) 1991 are shown in Figure 4.11. On the soil constructions pH fell from mean values of 6.0 to 5.6 as nitrogen fertiliser rate was increased from 35 to 635 kg N ha^{-1} yr^{-1}. The soil construction values showed no significant effects of phosphate fertiliser on soil pH. On the SWT constructions, pH was consistently lower on the USGA constructions at nitrogen rates of 235, 410 and 635 kg N ha^{-1} yr^{-1} with and without phosphate fertiliser. Rootzone pH declined initially and then increased as nitrogen fertiliser rates were increased. The nitrogen rates at which pH reached minimum values were 110 for sand constructions not receiving phosphate fertiliser, 235 kg N ha^{-1}

yr^{-1} for sand constructions receiving phosphate, between 235 and 410 kg N ha^{-1} yr^{-1} for USGA constructions not receiving phosphate and 410 kg N ha^{-1} yr^{-1} for USGA constructions receiving phosphate. The minimum pH was 4.1, on the USGA constructions receiving phosphate fertiliser and a nitrogen rate of 410 kg N ha^{-1} yr^{-1}, and the maximum was 5.4, on the sand constructions receiving no phosphate fertiliser and nitrogen at a rate of 635 kg N ha^{-1} yr^{-1}.

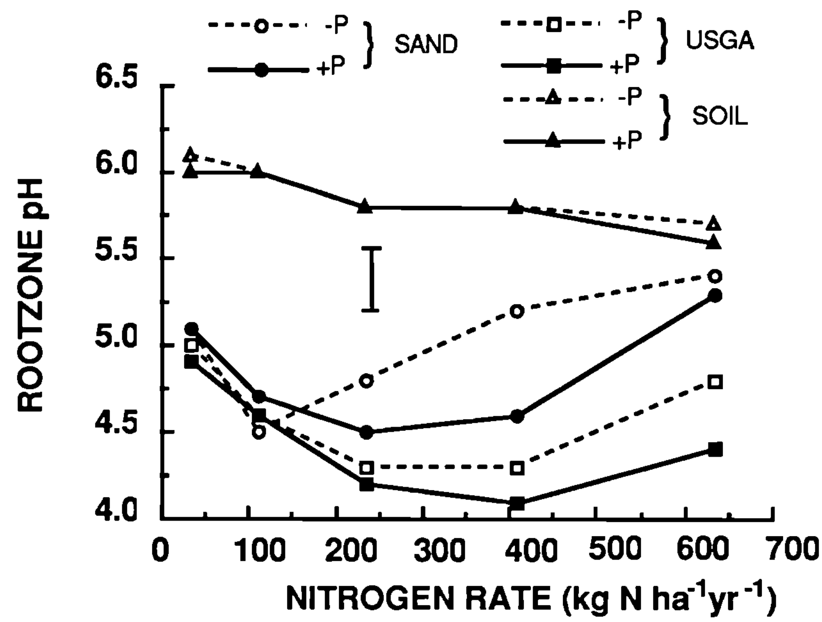

FIGURE 4.11
The effects of 5 rates of nitrogen fertiliser application with and without phosphate fertiliser on rootzone pH of the three construction types in week 41 (October) 1991. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means.

The effects of nitrogen and phosphate fertiliser on measured phosphate content of the rootzones of the three constructions are shown in Figure 4.12. Phosphate levels generally declined with increasing rate of nitrogen fertiliser, an effect which was most apparent between 35 and 235 kg N ha^{-1} yr^{-1}. Levels were consistently greater on SWT sub-sub-plots treated with phosphate fertiliser. Phosphate and nitrogen fertiliser treatments had no significant effects on measured phosphate content of the soil constructions in week 41 (October) 1991.

In week 41 (October) 1991 rootzone potassium content declined consistently on all three construction types with increasing rate of nitrogen fertiliser. These data are shown in Figure 4.13.

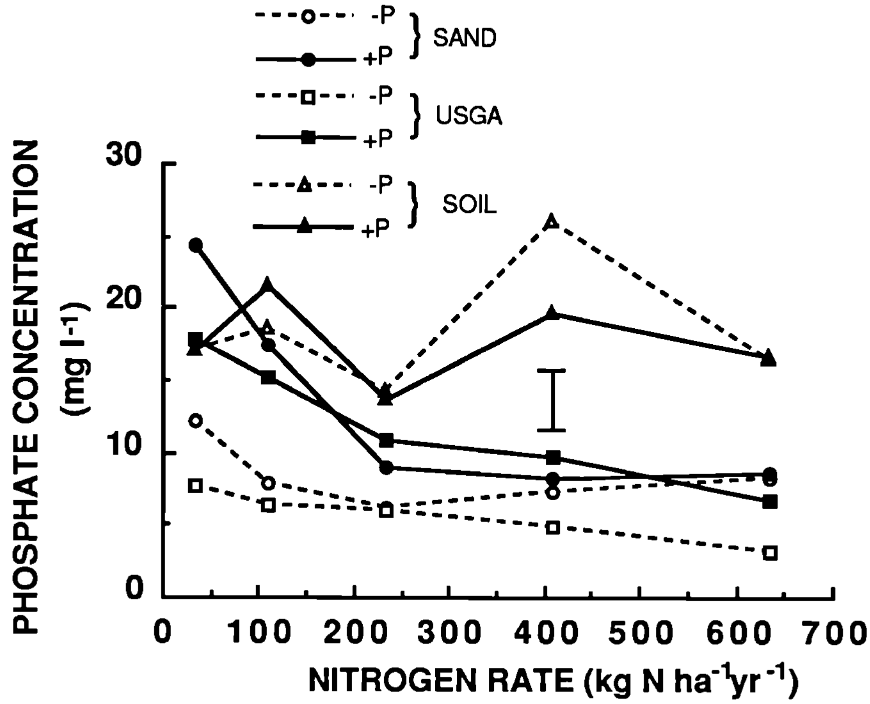

FIGURE 4.12
The effects of 5 rates of nitrogen fertiliser application with and without phosphate fertiliser on rootzone phosphate content (0.5 M acetic acid extract) of the three construction types in week 41 (October) 1991. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

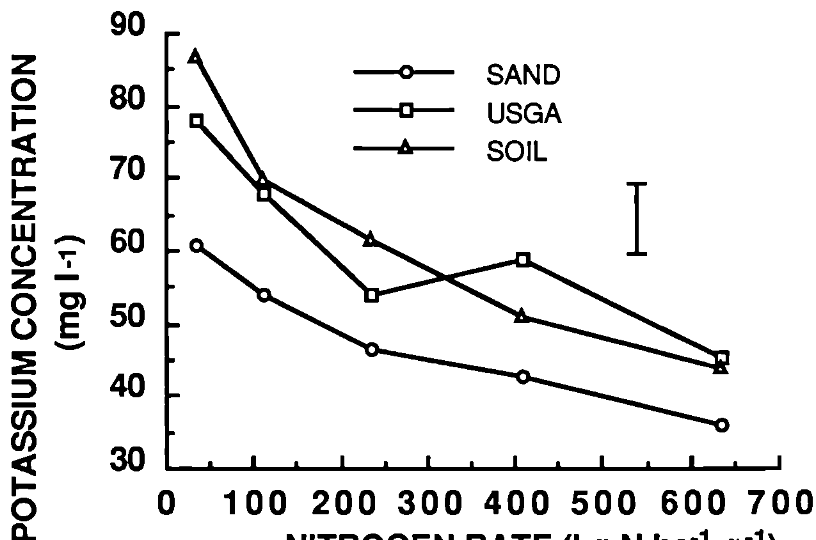

FIGURE 4.13
The effects of 5 rates of nitrogen fertiliser application on rootzone potassium content (0.5 M acetic acid extract) of the three construction types in week 41 (October) 1991. Vertical bar represents LSD ($p \leq 0.05$) for comparing all possible pairs of means presented.

4.4 DISCUSSION

The differing species contributions arising from the same seed mixture (see Section 2.6) on the three construction media prior to the application of fertiliser and irrigation treatments may have come about through differing rates of germination of each species on each construction. The sizes of the seeds of *F. rubra* and *Agrostis* spp. are markedly different. The original 80 : 20 mix of the two species actually produced a seed number ratio of 1 *F. rubra* : 3.7 *Agrostis* spp. (from the data of Shildrick 1984). Thus if germination rates were equal, *Agrostis* spp. would be expected to possess an initial numerical advantage over *F. rubra*. But the fact that the larger-seeded, and therefore initially more self sufficient, *F. rubra* established to a greater extent on the sand constructions, while the greater numbers of tiny seeds of *Agrostis* spp. established more quickly on the inherently more fertile soil constructions, may point to the influence of differential fertility levels influencing the respective development of differing seed species before and after germination.

Immediately prior to differential treatment application, the total ground cover had not reached 100 % on any construction type which may indicate that inter- and intra - specific competition for resources was not the overriding limiting factor, but that differential rates of establishment and early growth were of greater significance. It is not possible to say, on the basis of these data, at what point and by what means in the early stages of grass development from dormant seed, the different construction types exerted their influence. The subtlety with which different substrates affect germination and establishment have been demonstrated for many species (see Harper (1977) for an extensive discussion) and a study of turfgrass species germination alone could fill several very interesting theses. The game of golf is concerned with established turf only, and the mechanisms by which differing construction media influence final sward composition are consequently of limited significance. *F. rubra* is considered to be a highly desirable component of golf green swards (Anon. 1989b). These observations may therefore suggest that further research be carried out examining the effects of varying sowing mixtures and rootzone media on established sward species composition.

The general decline in *F. rubra* cover on all three construction types over the trial period may have arisen through straightforward inability of the species to sustain growth under the environmental conditions imposed. The greatest general, proportional decline in *F. rubra* cover took place over the winter of 1990/91, during which the weather was particularly harsh and wear treatments had begun to be applied. *Agrostis* spp. also declined over this period, but recovered the following growing season, a recovery which *F. rubra* failed to achieve. Canaway (1978) found that *F. rubra* was slightly more wear tolerant in monoculture than *Agrostis* spp. These data may therefore indicate that turfgrass wear tolerance is controlled by a different set of processes to the recovery from wear (or any other "catastrophic" event). *Agrostis* spp. would appear to be more vigorous with respect to *F. rubra* in the recovery from wear.

On the soil constructions, this recovery period coincided with a rapid expansion in *P. annua* cover which took place chiefly at the expense of *Agrostis* spp. The weed may therefore be considered as having colonised the space created by the winter decline of 1990/91. Lush (1988a & b) observed that *P. annua* initially colonised bare patches brought about by disturbances in the surface of golf greens. Lush suggested that the balance finally achieved between *Agrostis stolonifera* (sown in the swards studied) and *P. annua* in any particular green, reflected the possibility of such disturbances taking place. The studies of Lush were carried out on a real golf green which was subjected to play and the random occurrences of disturbances. In the work described here, random disturbances were kept to a minimum. Since the soil construction rootzone was sterilised prior to sowing, the occurrence of *P. annua* must have come about mainly through the successful establishment and growth of incoming *P. annua* propagules, most probably seeds, rather than the recruitment of seeds from a seed bank in the soil. The widely differing degrees of *P. annua* ingress on the three construction types must therefore have come about through the differential effects of the rootzone media on *P. annua* germination and establishment.

Again, the identification of the exact features of differing rootzone media which determine the suitability or otherwise for the successful germination and early growth of *P. annua* would represent a major study. Possible areas of investigation might include the effects of differential moisture potentials, substrate structure and texture, surface microtopography, specific heat capacity, pH, and organic matter and nutrient content. All these features clearly vary between construction media. One feature worthy of consideration is that the seed of *P. annua* is approximately 27 % in weight that of *F. rubra*, whereas *Agrostis* spp. seed is only 7 % of that weight. If seed size is of significance in determining germination success in grasses, as was proposed by Kittock & Patterson (1962), then the proportionately larger size of *P. annua* seeds may provide sufficient resources to quickly establish a newly arrived plant as a competitor in established turf, provided the rootzone is hospitable to germination. Given that *P. annua* is so ubiquitous and is usually, though not always, considered to be an undesirable component of golf green swards, studies specifically aimed at identifying the main environmental or edaphic determinants of its germination may indicate useful techniques for the control of its infestation of golf greens.

The substrate determinants of germination are not necessarily the same factors which influence plant and community development. As the individual plant grows it exploits larger volumes of space within the environment of the green and is therefore subject to the modifying influences of larger numbers of environmental variables, some of which were measured in this study. In addition, competitive interference processes take place as the "spaces" of individual plants merge with those of neighbouring plants. Isolating any one environmental feature and associating it with a particular sward characteristic is therefore extremely difficult and requires precisely targetted experiments in order to do so. A major objective of this research however was to generate hypotheses which may subsequently be tested with such experiments, and these data invite many such hypotheses.

The increasing *Agrostis* spp. cover and decreasing *F. rubra* with increasing rate of nitrogen application was not unexpected and has been reported several times (Skirde 1974, Woolhouse 1981, Lawson 1987, Lodge *et al.* 1990). The transition was not a simple displacement of one species by another however. Changes in the cover of litter (dead material) accounted for the greater part of the changes in *Agrostis* spp. cover on the suspended water table constructions. Plant death was associated with both high and low rates of nitrogen fertiliser, low rates of irrigation, and was especially apparent on the sand constructions not receiving phosphate fertiliser. These effects of high nitrogen have frequently been ascribed to over - acidification due to the acidic nitrogen source used (Skogley 1967, Robinson 1980). But, although the soil chemical data presented refer to the period 12 months before the October 1992 botanical composition data, the rootzone pH values actually increased on the SWT constructions in response to the higher nitrogen rates. The lowest pH values were recorded from the sub-sub-plots maintaining maximal live ground cover. Rootzone pH cannot therefore be considered in isolation as a factor affecting turfgrass survival.

The acidifying effects of ammonium sulphate application come about due to the nitrification of ammonium (NH_4^+) to nitrate (NO_3^-) by *Nitrosomonas* and *Nitrobacter* bacteria. This process releases H^+ ions which lowers the pH, a phenomenon clearly demonstrated by Duisberg & Buehrer (1954). Munk (1958) showed that low soil pH (pH 4.4 in his experiments) substantially depressed NH_4^+ oxidation, but Purchase (1974) showed that the nitrite oxidisers (*Nitrobacter*) were also very sensitive to phosphate deficiency. Therefore a possible reason why pH did not continue to fall at the higher nitrogen rates on the SWT constructions, a result expressed to a lesser extent on the phosphate-treated sub-sub-plots, may be that phosphate levels were reduced to a point which limited the nitrification process. Also, the decline in extractable phosphate may have been due to the ion becoming insoluble at the lower pH values and therefore not measureable.

Some of the death, or reduced vigour, of grass may have come about through phosphate deficiency itself. Symptoms of this could be seen quite clearly during the summer months as a purple tinge to the turf (Wild & Jones 1988). This was most apparent on sand and USGA construction sub-sub-plots receiving high rates of nitrogen and no phosphate. But the relatively high ground cover on the USGA sub-sub-plots receiving no phosphate and 235 kg N ha^{-1} yr^{-1} coincided with rootzone phosphate levels of less than 7 mg l^{-1}. This study indicates therefore, that rootzone phosphate levels alone, as measured by the technique described, cannot fully explain the botanical changes which took place and highlights the importance of examining rootzone texture and construction type when considering the effects of phosphate application to golf green turf.

The enhancing effects on grass death of nitrogen fertiliser at the lowest rate of irrigation may suggest that some soluble substance, normally leached out or further down the profile, accumulated to toxic levels in the rootzones. The nitrogen fertilisers used were very soluble in water. The high rates of application may therefore have raised the osmotic potential of the rootzones to damaging levels. This hypothesis agrees with the observation that plant death was greatest on the USGA constructions which also showed the greatest soil moisture deficits (Chapter 3) at the height of summer.

When water and phosphate fertiliser were not limiting, ground cover remained high with nitrogen rates of up to 410 kg N ha^{-1} yr^{-1} . Depletion of rootzone phosphate and potassium may therefore have come about by nitrogen - stimulated growth and removal of clippings. This was proposed by Colclough & Lawson (1989). The seasonal changes in potassium content appeared to follow the pattern of increasing during the growing season, when "luxury" rates of the ion were supplied, and declined during the winter when leaching losses will have taken place. A similar effect was reported by Childs & Jencks (1967). This is consistent with the view that rootzone potassium content is controlled by the nature and extent of the cation exchange sites on clay minerals and organic matter. A mechanism therefore exists for the progressive loss of potassium by equilibration in the soil solution of potassium from exchange sites, through-flow of water and re-equilibration. The significant effects of the irrigation treatments on rootzone potassium levels supports this.

However, seasonal variation was not observed in the rootzone phosphate levels. Phosphate levels in the soil solution are, by contrast with potassium, extremely low, being of the order of 0.5 mg l^{-1} (Wild 1988b). The lack of response to irrigation treatments and lack of seasonal variation of rootzone phosphate levels may therefore be due to the readiness of the ion to be retained on surfaces in the rootzone. That phosphate levels were lowest on the sand constructions may reflect the smaller area of mineral surface to which phosphates may have adhered, and the smaller quantities of organic matter from which it may have been released by mineralisation. In general, the soils might have been expected to have a very high phosphate buffering capacity (Olsen & Watanabe 1970), and the sand constructions a low one. In this respect the botanical composition changes in response to the phosphate fertiliser treatment illustrated the effects of phosphate buffering. Thus, both total live cover and cover-adjusted shoot density responded greatly to phosphate fertiliser application on the sand constructions, while the USGA constructions, which contained a little organic matter and more mineral surface than the sands, responded slightly less so, and the soil constructions responded hardly at all.

Some research has suggested that the application of phosphate fertiliser encourages the ingress and development of *P. annua* (Goss *et al.* 1975, Waddington *et al.* 1978). These suggestions were barely supported by these findings. Phosphate fertiliser had no significant effect on *P. annua* cover for example. Considering the soil construction sub-sub-plots as representatives in time of a series of successional changes, it might be predicted that *P. annua*, which was present in all soil sub-sub-plots, will continue to expand in cover and eventually totally dominate the swards. The speed of this expansion would appear to be a function of the nitrogen input alone. Phosphate levels in the soil were however consistently higher than on the SWT constructions, from which *P. annua* was virtually absent. Confusion may have arisen due to a general failure by research workers to acknowledge the effects of rootzone texture or, more specifically, of buffering capacity. Thus, if *P. annua* is able to establish on a rootzone with a low phosphate buffering capacity, the efficacy of phosphate fertiliser in stimulating growth may result in enhanced development of *P. annua* cover. This may take place due to the enhancement of shoot density and competitive vigour in general, in the same way in which both nitrogen and phosphate fertiliser appeared to enhance the growth of *Agrostis* spp. at the expense of *F. rubra* on the SWT constructions, and nitrogen alone enhanced develpment of *P. annua* at the expense of *Agrostis* spp. on the soil constructions. The continuation of the trial for a few more years may have some merit in this respect. The possible influences of phosphate fertiliser on the development of *P. annua* on the SWT constructions may then be observed.

CHAPTER 5 - THE GOLF BALL IN PLAY

5.1 INTRODUCTION

In order to assess the ways in which the differential treatments affect the green in terms of their influence on playing quality, it is necessary to simulate the behaviour of golf balls in play. As far as the green is concerned, this involves the simulation of putting and of ball impacts.

The "standard" putt produced by the Stimpmeter (Stimpson 1974, Radko 1977a, b, 1978) is commonly used to produce the rolls for the measurement of green "speed". This may be defined as the distance which a golf ball travels across the surface of a green after being projected at a given velocity. The Stimpmeter consists of a straight, v-shaped aluminium ramp down which a ball is rolled. The ball is placed in a notch near the top of the ramp and the ramp is then tilted forward. When the ramp reaches an angle of about 22° to the horizontal, the ball falls out of the notch and rolls across the turf with an initial speed of 1.9 m s^{-1} (Haake 1989). The distance travelled by the ball from the end of the ramp is taken as a measure of the turf speed. This device was used by Engel *et al* (1980), Colclough (1989) and Baker and Richards (1991) to assess the effects of various construction and maintenance procedures on golf greens.

During the present study a number of problems and concerns arose with respect to the use of the Stimpmeter. Firstly, the roll of the ball after leaving the Stimpmeter in some cases was found to exceed the length of the diagonal of the 2 m x 2 m plots used in the trial. Secondly, the observed effects of treatments on golf ball roll induced by the stimpmeter may have been confounded by effects on the downward impact of the ball onto the turf brought about by the instantaneous change of direction of travel at the base of the ramp. Also, the v-shaped section of the Stimpmeter made two points of contact with the ball and thus imparted topspin as the ball descended the ramp. The manner in which this affected ball roll distance on different surfaces was unknown and may have led to confusion between spin retention and ball roll phenomena in the data. Finally, in the research situation, which demanded repeated measurements of green speed, the Stimpmeter is slow and there was the possibility of variation in the initial Stimpmeter release angle as a result of operator error which would result in increased variability in the measured green speed. In an attempt to address these problems, and hence reduce errors in the measurement of ball roll, an apparatus was designed for the measurement of green speed in research situations.

Turf phenomena which may influence ball roll were listed in Section 1.9. One such factor is the "upward" growth rate of the sward. Although golf greens are maintained at fairly consistent cutting heights, the growth rate may be such that effects on ball roll become apparent very soon after mowing. A measure of the rate of vertical growth, or clipping "yield", as it may affect ball roll, is readily obtained from the fresh weight of clippings produced after mowing. If the treatment effects on this feature show a similar pattern to those on ball roll, a relation between ball roll and rate of upward growth may be indicated.

Considering chip and drive shots onto the green, the chief criterion of concern to the player is the total distance travelled by the ball after impact. This was measured by Colclough (1989) and termed "holding power". In order to understand more fully how management factors affect this property, it is necessary to consider other characteristics of rebound. Haake (1991a,b,c) developed an apparatus to project consistent, simulated shots. He put forward a physical model which partially described the post-impact behaviour of balls hitting turf with backspin at oblique angles. This required five input parameters, four of which were to derive the rebound velocities of non-spinning, vertical impacts. The fifth was the coefficient of turf friction which modified the model to account for the interaction between the backspin of the ball and the green. Suitable values for these constants were derived by iterative searching procedures and tested against observations of actual impacts recorded on film. The derivation of the five input parameters, and Haake's model itself, is complex and the testing apparatus extremely cumbersome. If statements about the golf ball impact characteristics of a particular green are to be made, it would be advantageous if they were based on a few readily obtainable measurements.

The fifth parameter of Haake's model, the coefficient of turf friction, was related to the horizontal moments of a spinning golf ball impacting at an oblique angle. An apparatus which may provide an indication of the forces acting on the horizontal moments of the motion of impacting golf balls is one designed to measure soil shear strength in the surface layers of the turf with which the ball interacts. The other input parameters of the model pertained to factors related to the reaction of the turf to the vertical moments of the ball's motion. A readily measured feature which may provide a summarised indication of these parameters is that of hardness. Colclough (1989) measured the hardness of fine turf using a Clegg Impact Soil Tester (Clegg 1976). Hardness is known to have an influence on the impact behaviour of footballs (Baker and Isaac 1987, Bell and Holmes 1988) and cricket balls (Lush 1985). Colclough (1989) found that hardness declined with increasing nitrogen input and, like stopping distance, was greater in un-limed plots.

In this study, the relationships between measured aspects of post-impact ball behaviour, hardness and shear strength were therefore explored.

The various aspects of post-impact ball behaviour which can be measured are clearly inter-related in a complex manner. One method of reducing a large set of inter-related measured variables to a smaller, more manageable set is to use the method of principal components analysis (PCA) (Hotelling 1933, Chatfield & Collins 1980). This multi-variate technique uses the correlation matrix of measured variables to project stands onto a single line such that the sum of squares of their distances from the line is minimised. The distances of the stands from the first axis are then used to derive stand positions on an orthogonal second axis. The reference axes of the data set are thus changed to a new orthogonal framework, the origin of which represents the centroid of the whole set of stands.

The first axis or principal component has maximum correlation with the data variables, the second also has maximum correlation with the data variables but is uncorrelated with the first. A complete description of the data would require as many axes as there are variables in the data. However, the method concentrates the variability such that the first axis accounts for the largest proportion of the variation in the data set, and subsequent axes account for proportionately less and less variation. Later-derived axes may therefore be ignored because they represent only a fraction of the original variation.

Each measured variable has a characteristic component loading in relation to each axis. Variables with similar distributions among the stands being analysed will have similar component loadings which provide the coordinates of an ordination of variables using the same axes as those derived for the stands. The relationships between variables may therefore be observed by plotting the measured variable coordinates on the derived components or axes. This form of diagram is known as a biplot. The coordinates of each measured variable in relation to the centroid or origin indicate the direction and extent to which that variable is associated with the axis concerned. A general impression of how the variables inter-relate and of what each derived axis, or component, actually represents may be obtained from the biplot. The effects of treatments may then be examined by performing ANOVA on the individual plot scores in relation to each axis.

In this chapter, the effects of the treatments on ball roll characteristics are examined alongside measurements of clipping "yield". Treatment effects on simulated golf ball impacts are also examined, and the possibility of using simple measures such as hardness and shear strength to summarise the nature of golf greens with regard to golf ball impacts is explored.

5.2 MATERIALS AND METHODS

Ball roll apparatus and test methods

The apparatus consisted of a ramp fabricated from 50 mm bore, 4 mm guage steel tubing which had been cut longitudinally in half. The overall length of the ramp was 1020 mm. Beyond a distance of 20 mm from the lower end, the ramp was curved to produce an arc of length 100 mm and radius 286 mm. This made an angle of 20° between the remaining 900 mm of the ramp and the horizontal. These features are shown in Figure 5.1. The 20 mm horizontal section of the ramp was ground to a fine edge around the bottom of the semi-circular cross section to bring about a smooth transition from the end of the ramp onto the turf. The apparatus was supported at the stated angles by means of two steel legs bolted to a tongue welded to the lower side of the ramp c. 20 mm from the top. After grinding the inner face of the ramp to a smooth surface the whole apparatus was coated with several layers of a tough, gloss lacquer.

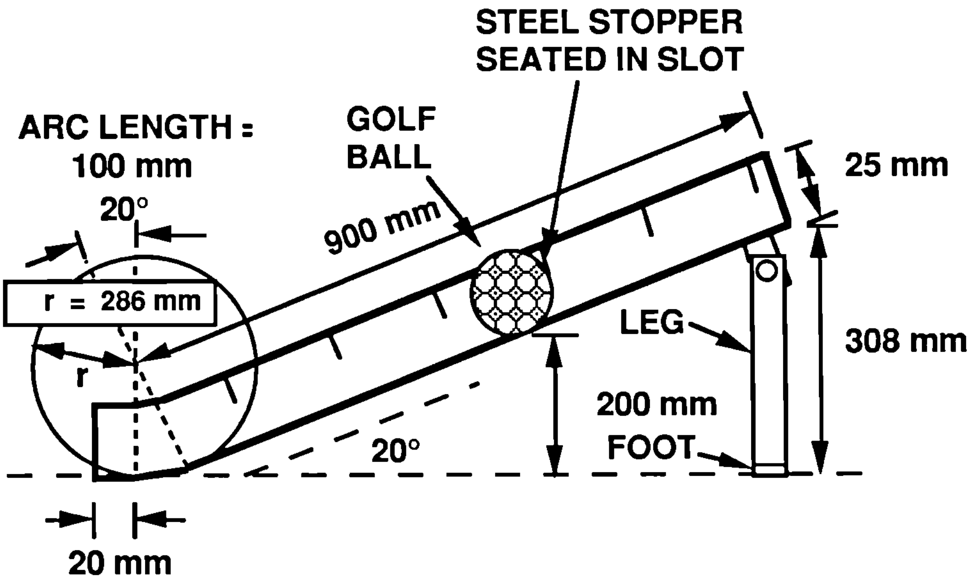

FIGURE 5.1

Schematic diagram of golf ball roll ramp showing dimensions of individual components.

Fine slots were cut in opposite edges of the ramp to house a removable steel strip which could be used to set the release height of the ball. Slots were cut such that releases could be made from heights of 50, 100, 150, 200, 250 and 300 mm from the lowest point of the ball to the ground.

The gradual curve at the base of the ramp was designed such that no more than one point of contact was made between a Titleist 384 90 golf ball and the ramp during the ball's journey down the ramp and the transition onto the turf. Similarly, the internal diameter of the ramp was chosen to minimise lateral movement of the ball during descent, whilst maintaining a single, central plane of revolution of the ball and avoiding the development of topspin.

Following tests involving repeated rolling of Titleist 384 90 wound golf balls from each release height over a level, uniform, artificial turf surface, it was found that roll length increased linearly over the range between 50 and 300 mm. This linear relationship was expressed by the equation:

$$y = 6.59x + 22.9 \quad (r^2 = 0.995) \qquad (5.1)$$

in which x was the roll ramp release height (mm) and y was the distance (mm) between the end of the ramp and the final resting place of the ball.

On the trial it was found that the release height of 200 mm produced rolls which consistently remained within the confines of the sub-sub-plots. Two balls were rolled from this height across the diagonal in both directions on each of the 90 sub-sub-plots in one block of the trial after mowing at 5 mm. The same procedure was carried out immediately afterwards using a Stimpmeter. This was performed in week 27 (July) 1991 when the turf had fully established and a great deal of heterogeneity of turf types existed on the trial due to the imposition of the treatment factors.

Using the mean distance travelled of the four readings for each sub-sub-plot, simple linear regression of the ramp speeds was carried out on the Stimpmeter speeds. This showed a highly significant ($p \leq 0.0001$), linear relationship between the two measures. The equation for the line was;

$$y = 0.973x + 0.675 \quad (r^2 = 0.778) \qquad (5.2)$$

in which x was the roll ramp speed (m) and y the Stimpmeter speed (m). Substituting the mean Stimpmeter value obtained from the 90 sub-sub-plots into Equation 5.1, the equivalent release height required to produce Stimpmeter-like rolls was found to be 352 mm. For roll ramp distances within a range of about 1.5 m to 3.0 m, Equation 5.2 may be used to convert roll ramp distances to the more commonly quoted Stimpmeter values, or *vice-versa*.

During practical use, the ramp was found to be considerably quicker to use than the Stimpmeter in circumstances in which repeated measurements needed to be made. Maintaining a clean and dry inner face of the ramp was essential, since foreign bodies on its surface collected in the centre of the semi-circular cross section where contact with the rolling ball was made.

Ball roll or green 'speed' was measured using the steel ramp described above. Balls were released down the ramp through a vertical height of 200 mm. Two balls were rolled across a diagonal of each 2 m x 2 m plot in opposing directions and the mean distance travelled of the four readings was used in the analysis. A method, put forward by Brede (1991), of correcting the distorting effects of downslope gravitational accceleration in the calculation of mean green speed values was not applied. This was because the mean slope diagonally across each sub-sub-plot was less than 1 %, and therefore such a correction, according to Brede, would have produced no significant improvement in accuracy. Roll assessments took place as soon as possible after mowing at 5 mm when the surface was not wet with rain or dew.

Clipping yield

Total clipping yields (fresh weight) were measured by weighing the clippings obtained from a powered pedestrian mower with the blades set at 5 mm applied to each sub-sub-plot after the trial had been left unmown for 5 days.

Golf ball impact studies

Golf ball impacts were simulated using a firing device developed from a baseball practice machine (Haake 1987, 1989, 1991a). Balls were projected with a backspin of approximately 770 rad s^{-1} (7162 rpm), a velocity of 22 m s^{-1} at an angle of 53°. These settings represented typical impact criteria obtained from a 5-iron shot delivered by a "scratch", professional golfer (Haake 1989) and generally ensured that projected balls remained within the sub-sub-plots after impact.

Several aspects of the behaviour of the ball following impact were recorded. Post-impact behaviour was divided into two phases, the bounce and the roll. The bounce phase was considered to be the movement of the ball after the initial impact until it next made contact with the ground. This trajectory may be assumed to be parabolic. As such it may be fully described in terms of the angle and velocity of rebound. Thereafter it was assumed for convenience that the ball travelled across the surface, although subsequent smaller bounces may have taken place.

The position of the end of the first bounce was located by eye. A second worker recorded the height of the bounce to the nearest 50 mm by reading off from a scale painted across an upright 2 m x 2 m board placed close to the plane of travel of the ball. The lengths of the bounce, the roll and the overall distance travelled by the ball were then measured.

Since the ball may have deviated from its initial direction of travel after impact, the check distance ("screw back" or "roll on"), in the line of travel of the ball after the first bounce, was calculated from the distance measurements by triangulation. Negative values of this indicated that the ball doubled back at the end of the first bounce.

The velocity (v) and angle of rebound with regard to the horizontal was estimated by triangulation of the vectors for horizontal (u_x) and vertical (u_y) velocities. The vertical velocity (u_y) was found from the equation for linear motion (Equation 5.3):

$$u_y^2 = u^2 + 2\,g\,s \qquad (5.3)$$

in which g = acceleration due to gravity (9.8 m s^{-1}) and assuming that the vertical velocity (u) at the maximum height reached (s) was 0 m s^{-1}. The horizontal velocity was then calculated by solving the trajectory equation (Equation 5.4) for u_x using half the bounce length (x) and the bounce height (y):

$$y = u_y\, x/u_x - 1/2\; g(x/u_x)^2 \qquad (5.4)$$

The depth of the pitchmark for each impact was also measured using a USGA greens hardness tester by the method described by Haake (1989).

Surface hardness was measured using a Clegg Impact Soil Tester (Clegg 1976). A 0.5 kg impact hammer was dropped down a guide tube through a height of 300 mm and an accelerometer in the hammer recorded the deceleration in gravities. Shear strength was measured using a Geonor Inspection Vane Borer (Geonor AS, Oslo, Norway). This consisted of a steel shaft to one end of which was attached a four-bladed vane. The gradual turning of a handle attached to the other end of the shaft exerted a torque which was measured with a spiral spring housed in the handle. The smallest of a series of vanes was selected. This consisted of four blades each 20 mm wide by 40 mm long, and measured shear strength in the range 0 to 20 t m^{-2}. The vanes were inserted into the turf so that their upper edge just disappeared below the surface. The handle was then slowly turned at constant speed until the handle followed the vanes around or fell back to a lower torque reading. This occurred when the shear strength of the rootzone failed under the force applied by the turning of the handle. Maximum shear strength was then read off the graduated scale. The mean of five tests per plot for both hardness and shear strength was used in the analysis.

The ball roll studies described in this chapter were carried out in weeks 13 (March), 21 (May), 31 (July) and 41 (October) 1991. Clipping yield fresh weight assessments were carried out in weeks 23 (June) and 31 (July) 1992. The ball impact tests were carried out in weeks 21 (May) and 30 (July) 1992 when each constuction type had received 33 and 67 % of the annual nitrogen application. For both ball roll and impact measurements, the type of golf ball used was a Titleist 384 90 wound ball. Principle components analysis (PCA) of the key measured variables (namely the total distance travelled, u_x, u_y, v, the check distance and the pitch-mark depth) was performed in order to indicate more clearly any inter-relationships between post-impact measurements which might exist. ANOVA was subsequently carried out on the resulting factor scores, and correlations between ball behaviour measurements and botanical composition data (Chapter 4), hardness and shear strength were calculated.

5.3 RESULTS

Ball roll and clipping yield tests

The effects of the nitrogen and phosphate fertiliser treatments on the mean ball roll of all four assessments carried out in 1991 on the SWT constructions (sand and USGA) is shown in Figure 5.2. Ball roll declined at a diminishing rate with increasing nitrogen input on both constructions treated with phosphate fertiliser. On sand construction sub-sub-plots not receiving phosphate fertiliser, this decline was much less marked. At the highest rate of nitrogen fertiliser, the USGA sub-sub-plots not receiving phosphate fertiliser showed a slight increase in ball roll.

Ball roll on the soil constructions showed a decline at a diminishing rate with increasing rate of nitrogen fertiliser. This is shown in Figure 5.3. This reponse showed no significant interaction with either phosphate fertiliser treatment or rate of irrigation.

The effects of nitrogen and the three irrigation treatments on ball roll on the sand and USGA constructions are shown in Figures 5.4 and 5.5 respectively. Both constructions showed an increase in ball roll at the higher rates of nitrogen fertiliser and with decreasing rate of irrigation. This increase was greatest on the sand constructions. The interaction of construction type, nitrogen and phosphate fertiliser and irrigation treatment was significant ($p \leq 0.05$) and these data suggested that the increase in ball roll on sand constructions at high nitrogen fertiliser rates without phosphate fertiliser was greater at the lower rates of irrigation.

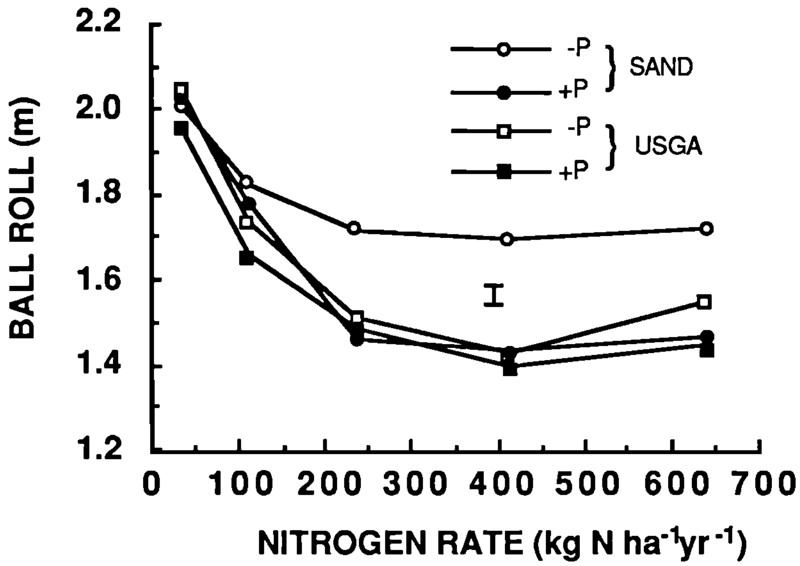

FIGURE 5.2

The effects of 5 rates of nitrogen fertiliser application on the SWT construction types, with and without phosphate fertiliser on mean ball roll (m) in 1991. Vertical bar represents LSD ($p \leq 0.05$) for the comparison of all possible pairs of means presented.

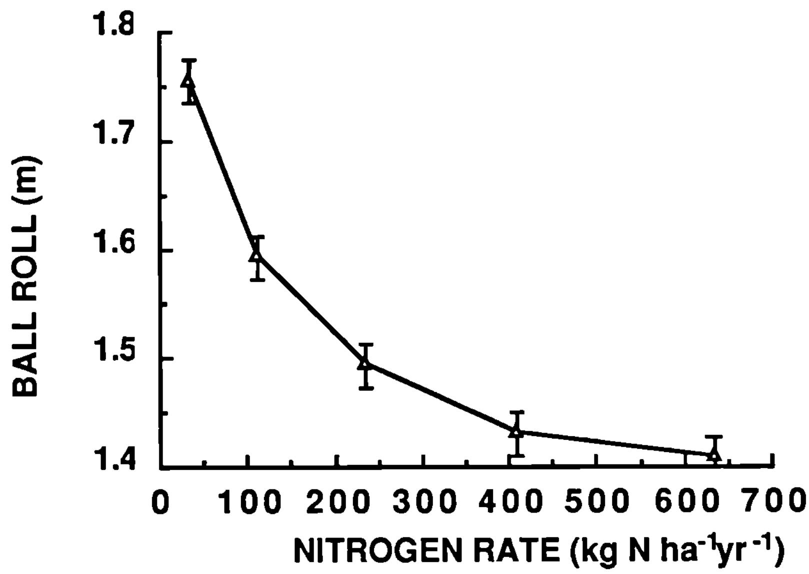

FIGURE 5.3

The effects of 5 rates of nitrogen fertiliser application on the soil construction type on mean ball roll (m) in 1991. Vertical bars represent standard errors (SEs) of the means presented.

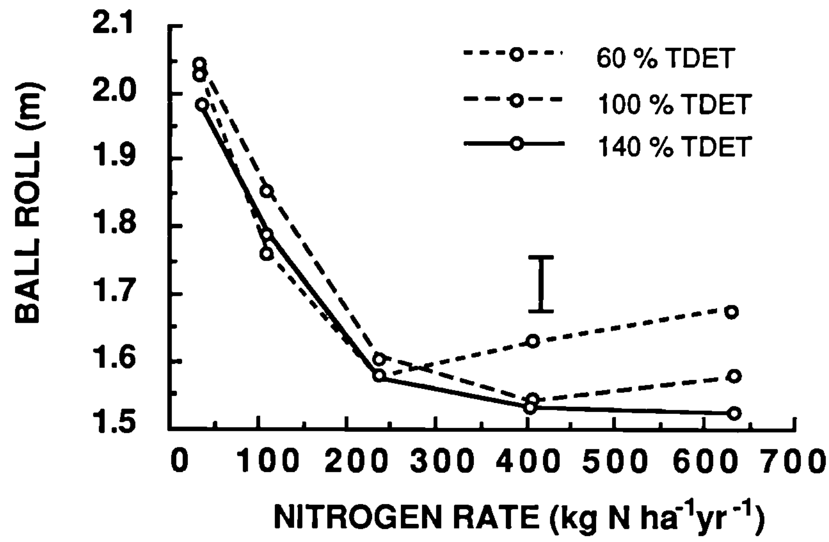

FIGURE 5.4
The effects of 5 rates of nitrogen fertiliser application on the sand construction type at three rates of irrigation on mean ball roll (m) in 1991. Vertical bar represents LSD ($p \leq 0.05$) for the comparison of all possible pairs of means presented.

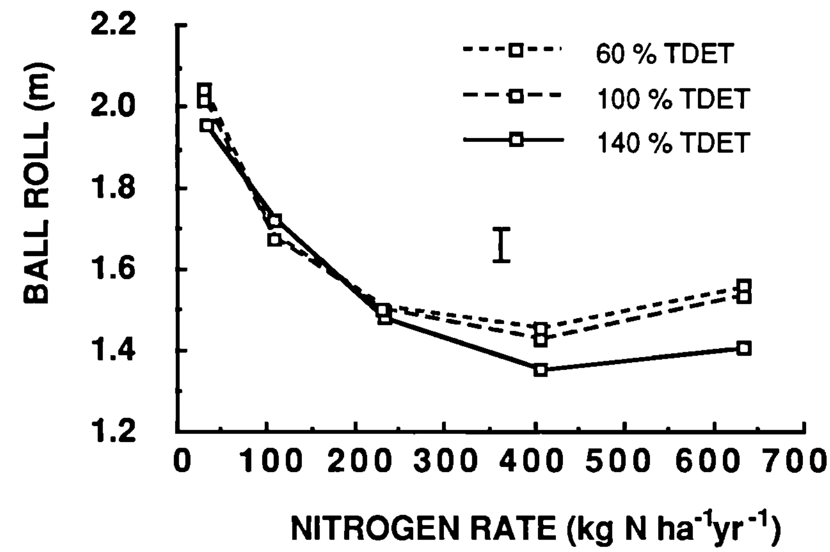

FIGURE 5.5
The effects of 5 rates of nitrogen fertiliser application on the USGA construction type at three rates of irrigation on mean ball roll (m) in 1991. Vertical bar represents LSD ($p \leq 0.05$) for the comparison of all possible pairs of means presented.

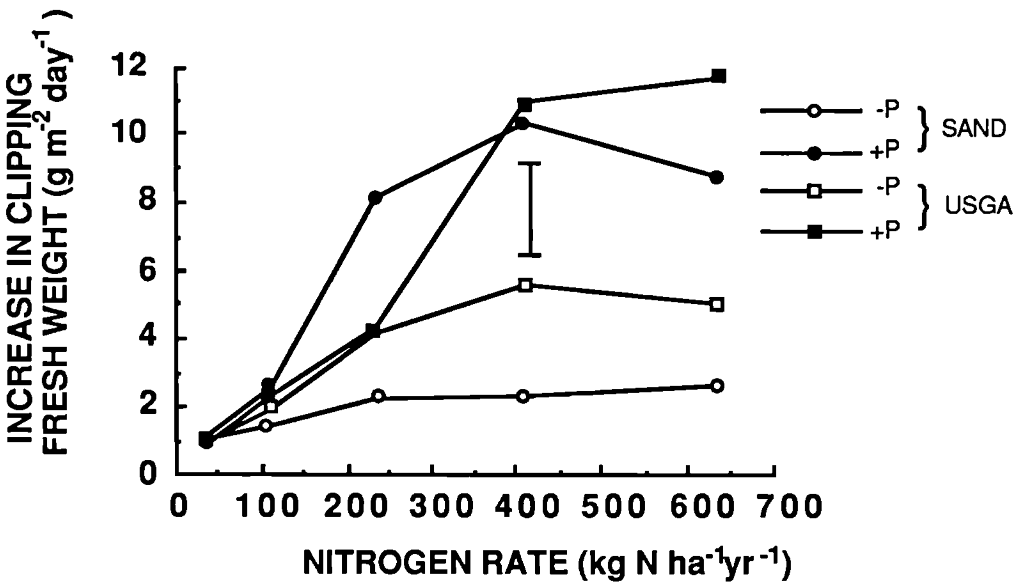

FIGURE 5.6
The effects of 5 rates of nitrogen fertiliser application on the SWT construction types, with and without phosphate fertiliser, on MCY (fresh weight) in weeks 23 (June) and 32 (July) 1992. Vertical bar represents LSD ($p \leq 0.05$) for the comparison of all possible pairs of means presented.

The effects of the nitrogen and phosphate fertiliser treatments on the mean clipping yield (MCY - described as fresh weight) of the two assessments carried out in 1992 on the SWT constructions is shown in Figure 5.6. Clipping yield showed a generally sigmoid increase with increasing nitrogen input on these constructions treated with phosphate fertiliser. On USGA sub-sub-plots not receiving phosphate fertiliser this increase was much less marked, and on the sand constructions yield increased only slightly. MCY on the soil constructions increased in a linear manner over the range of increasing nitrogen fertiliser. This is shown in Figure 5.7. This reponse showed no significant interaction with phosphate fertiliser treatment.

The interactive effects of construction type and irrigation rate on MCY are shown in Table 5.1. On the SWT constructions, clipping yield was significantly less ($p \leq 0.05$) on the underwatered (60 % TDET) plots.

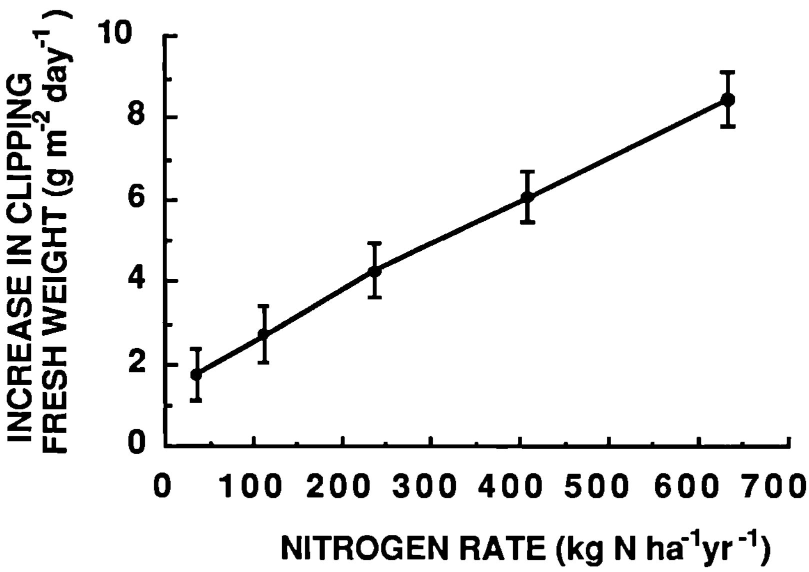

FIGURE 5.7
The effects of 5 rates of nitrogen fertiliser application on the soil construction type on MCY (fresh weight) in weeks 23 (June) and 32 (July) 1992. Vertical bars represents SEs of the means presented.

IRRIGATION RATE	SAND	USGA	SOIL
60% TDET	3.9	3.5	5.0
100% TDET	4.2	5.4	5.0
140% TDET	4.2	5.5	4.0
MEAN	4.1	4.8	4.7

TABLE 5.1
The effects of differing rates of construction and irrigation on clipping yield ($g\ m^{-2}\ day^{-1}$ - fresh weight) at a mowing height of 5 mm. These data represent the mean of two assessment carried out in June and July 1992. LSD ($p \leq 0.05$) for all means presented was 0.85.

The correlation coefficients of mean ball roll for all four 1991 assessments with the corresponding ground cover means of the two botanical composition assessments in 1991 (Chapter 4) are shown in Table 5.2. Total live cover was calculated as the net cover of *Agrostis* spp., *F. rubra* and *P. annua.* Ball roll was negatively correlated with total live cover, and its main component *Agrostis* spp, and positively correlated with *F. rubra.* Ball roll showed a negative correlation with *P. annua* cover, although the strength of the relationship was weaker than with other components of ground cover.

GROUND COVER	CORRELATION WITH BALL ROLL
Total live cover	-0.77
Agrostis spp.	-0.80
F. rubra	0.60
P. annua	-0.26

TABLE 5.2
Correlation coefficients of mean ball roll with the corresponding means of the two botanical composition assessments carried out in 1991. The least significant correlation coefficients for $p \leq 0.05$, 0.01, and 0.001were 0.195, 0.254, and 0.321 respectively.

Impact study data

The main effects of construction type and irrigation treatment on hardness, as measured with the Clegg Impact Soil Tester, were highly significant ($p \leq 0.001$). These data are presented in Table 5.3. Hardness increased with decreasing rate of irrigation and was greater on the soil constructions. The effects of irrigation were most apparent on the soil constructions and not at all apparent on the sand constructions.

IRRIGATION RATE	SAND	USGA	SOIL	MEAN
60% TDET	87	95	115	99
100% TDET	88	89	110	96
140% TDET	88	83	103	91
MEAN	88	89	109	-

TABLE 5.3
The effects of the construction and irrigation treatments in 1992 on turf hardness (gravities). LSD ($p \leq 0.05$) for the main effect of irrigation was 2.8 and for construction was 3.3.

Both the nitrogen and phosphate fertiliser showed similarly significant interaction ($p \leq 0.001$) with construction treatments. The effects of phosphate fertiliser on hardness of each construction are shown in Table 5.4. On the SWT constructions, the application of phosphate fertiliser reduced hardness.

CONSTRUCTION TYPE	PHOSPHATE TREATMENT ($kg\ P_2O_5\ ha^{-1}\ yr^{-1}$)	
	0	50
SAND	90	86
USGA	92	86
SOIL	109	110

TABLE 5.4
The effects of phosphate fertiliser on hardness (gravities) on each of the construction types. LSD for comparing all the means presented was 4.1, and for means with the same construction, 2.5.

The effects of nitrogen fertiliser on hardness of each construction type are shown in Figure 5.8. On all three construction types, hardness declined as nitrogen fertiliser rates were increased from 35 to 235 kg N ha^{-1} yr^{-1}. The extent of this decline was greatest on the soil constructions.

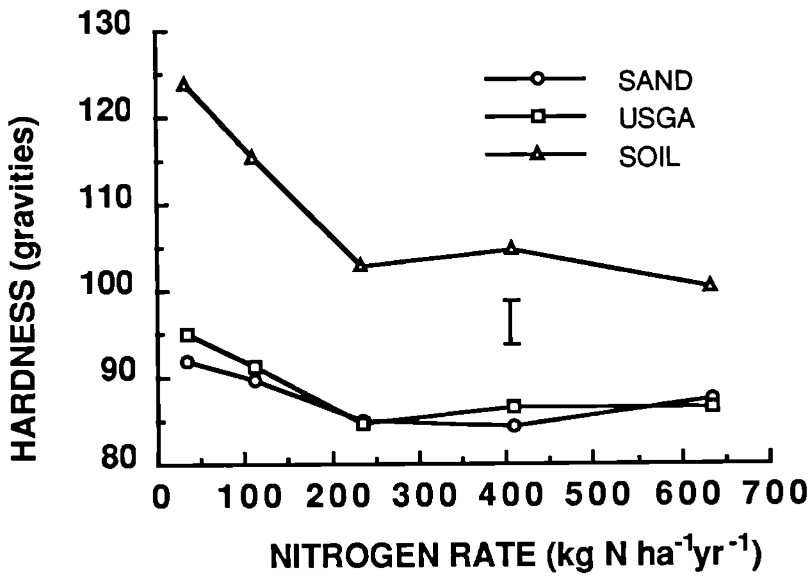

FIGURE 5.8
The effects of 5 rates of nitrogen fertiliser application on the three construction types on mean hardness (gravities) in 1991. Vertical bar represents LSD for comparison of all possible pairs of means presented.

Shear strength was greatest on the soil constructions. The mean shear strength values of the sand, USGA and soil constructions were 4.8, 5.5 and 9.4 t m^{-2} respectively. The LSD ($p \leq 0.05$) for the main effect of construction on shear strength was 0.87. On the sand constructions, the application of phosphate fertiliser significantly increased shear strength. The mean shear strength values of the sand constructions receiving phosphate fertiliser was 5.3 t m^{-2}, and of those not receiving it was 4.3 t m^{-2}. The LSD ($p \leq 0.05$) for this interaction was 0.51.

The main effects of the construction and irrigation treatments on the total distance travelled by golf balls after impact in both assessments carried out in 1992 are shown in Table 5.5. The soils gave the largest total distances. This declined with increasing irrigation rate. Nitrogen fertiliser had no effect on total distance travelled, either as a main effect or in interactions. On sub-sub-plots not treated with phosphate fertiliser, total distance travelled was significantly greater ($p \leq 0.05$, mean = 1.52 m) than on treated sub-sub-plots (mean = 1.38 m). The LSD for the main effect of phosphate fertiliser was 0.13.

IRRIGATION RATE	SAND	USGA	SOIL	MEAN
60% TDET	1.45	1.74	2.05	1.75
100% TDET	1.16	1.22	1.93	1.44
140% TDET	1.22	0.86	1.59	1.17
MEAN	1.22	1.27	1.86	-

TABLE 5.5
The effects of the construction and irrigation treatments in 1992 (mean of two dates) on the total distance travelled after impact by golf balls fired to simulate a 5-iron shot (m). LSD ($p \leq 0.05$) for the main effect of irrigation was 0.21, and for construction was 0.30.

The general inter-relationships between the aspects of post-impact ball behaviour in the 1992 assessments are given in the form of a correlation matrix, derived from the mean measures for each sub-sub-plot, in Table 5.6.

	TD	U_x	U_y	V	CD	PMD
Total distance (TD)	1.00					
U_x	**0.81**	1.00				
U_y	**0.49**	**0.71**	1.00			
Net velocity (V)	**0.60**	**0.83**	**0.98**	1.00		
Check distance (CD)	**0.63**	0.12	-0.25	-0.17	1.00	
Pitchmark depth (PMD)	**-0.38**	-0.06	0.31	0.24	**-0.69**	1.00

TABLE 5.6

Correlations amongst various aspects of golf ball behaviour after impact. Values of the correlation coefficient (r) for $p \leq 0.05$, 0.01 and 0.001 are 0.195, 0.254 and 0.276 respectively. Correlations significant at $p \leq 0.001$ are shown in bold.

Many of the correlations were significant ($p \leq 0.001$) though not very strong. These inter-relationships may be indicated more clearly using the biplot of the same component loadings obtained from the PCA. The first three axes derived by the PCA accounted for 59 %, 34 % and 5 % of the variation observed in the data. A biplot of the first and second axes (components I and II) therefore described 93% of the observed variation. This biplot, showing the inter-relations of the 6 measured features shown in the correlation matrix, is given in Figure 5.9.

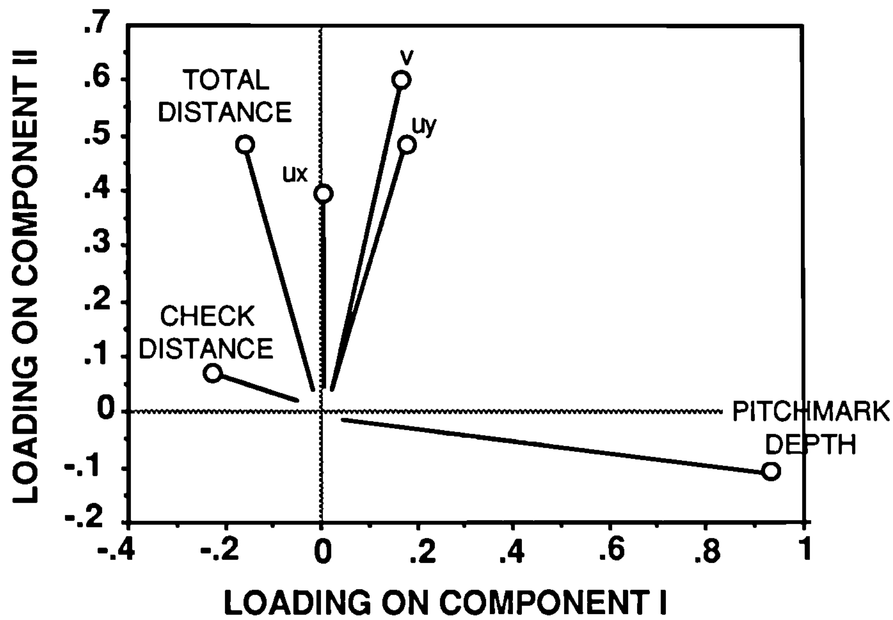

FIGURE 5.9

Component loadings of the 6 measured variables showing orientation with respect to the first two components derived by PCA from the golf ball impact data collected in 1992.

The observations most closely associated with Component I were pitchmark depth (PMD) and check distance (CD). These were strongly negatively correlated, indicating that as the Component I score declined, pitch mark depth became greater, the check distance was reduced and balls "screwed back" on themselves to a greater extent. The rebound velocity features (u_x, u_y and v) were most closely associated with the orthogonal Component II and were highly positively correlated with each other. Thus, as Component II scores declined, so did the rebound velocities. The total distance travelled by balls was most associated with Component II, but was also associated with check distance, in Component I, which comprised, of course, the second part of the ball's journey.

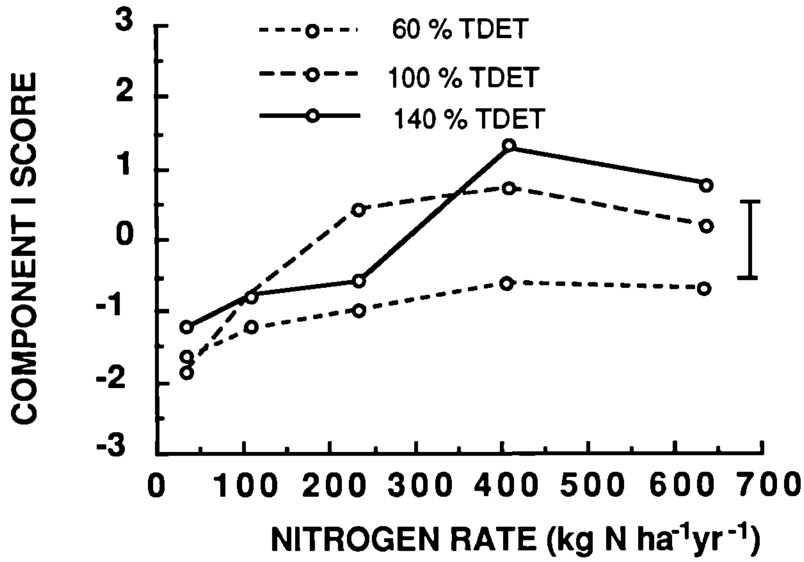

FIGURE 5.10

The effects of 5 rates of nitrogen fertiliser application on the sand construction type, at three rates of irrigation, on Component I score from the PCA of the ball impact data collected in 1992. Vertical bar represents LSD ($p \leq 0.05$) for all possible pairs of means.

The effects of the nitrogen and irrigation treatments on Component I scores for the sand and USGA construction types are shown in Figures 5.10 and 5.11 respectively. On the sand constructions, the 140 % and 100 % TDET treatments did not significantly differ at each rate of nitrogen fertiliser, but Component I scores were significantly less with the 60 % TDET treatment. Increasing nitrogen fertiliser gave a general increase in Component I score, and this increase was greater at the higher rates of irrigation. On the USGA constructions, the interactive effects of irrigation and nitrogen fertiliser were very pronounced. At the 60 % TDET irrigation rate, Component I scores were slightly greater at nitogen rates of 235 and 410 kg N ha^{-1} yr^{-1}. At 100 % TDET, scores increased with increasing nitrogen rate and appeared to level off above 235 kg N ha^{-1} yr^{-1}. At the highest rate of irrigation, scores continued to increase with nitrogen fertiliser to reach maximum values at 410 kg N ha^{-1} yr^{-1}.

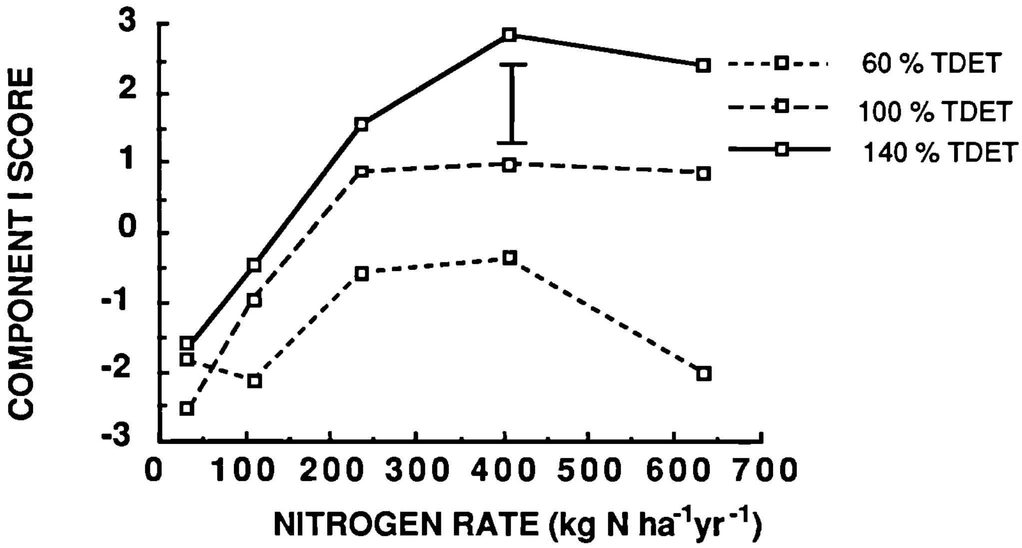

FIGURE 5.11

The effects of 5 rates of nitrogen fertiliser application on the USGA construction type, at three rates of irrigation, on Component I score from the PCA of the ball impact data collected in 1992. Vertical bar represents LSD ($p \leq 0.05$) for all possible pairs of means presented.

On the soil constructions, no significant interaction with irrigation treatment was observed with regard to the Component I scores. Scores showed a continuous increase with increasing nitrogen and this response is shown in Figure 5.12.

The phosphate fertiliser treatment showed a significant interaction with construction type with regard to Component I scores. The mean values are shown in Table 5.7. Phosphate fertiliser increased Component I scores on the sand and USGA constructions, but had no significant effect on the soil constructions. This increase was greatest on the sand construction.

The effects of the irrigation and nitrogen fertiliser and construction treatments produced differences in the Component II scores which were apparent as the main effect only. Increasing rate of irrigation showed a decrease in Component II score across all treatments. The mean scores for irrigation rates of 60, 100 and 140 % TDET were 0.24, 0.06, and -0.29 respectively, and the LSD ($p \leq 0.05$) was 0.27. The Component II score

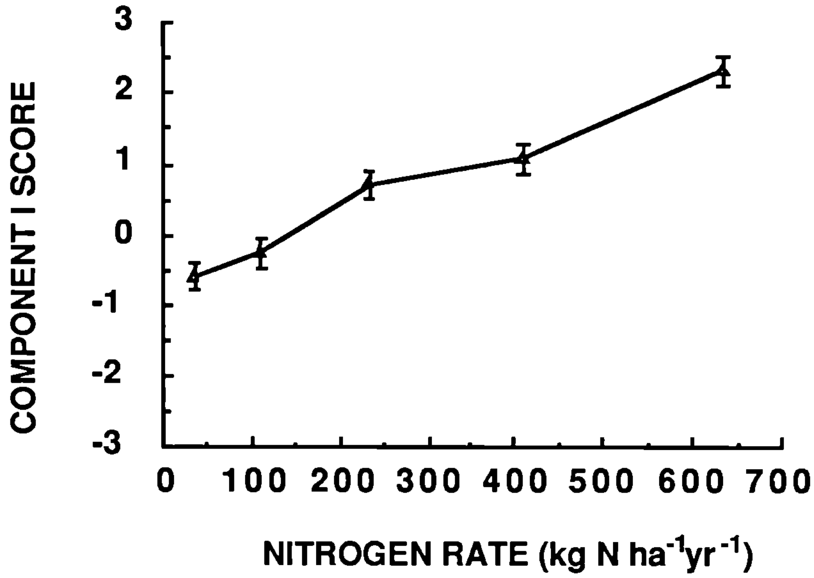

FIGURE 5.12

The effects of 5 rates of nitrogen fertiliser application on the soil construction type on Component I score from the PCA of the ball impact data collected in 1992. Vertical bars represent SEs of the means presented.

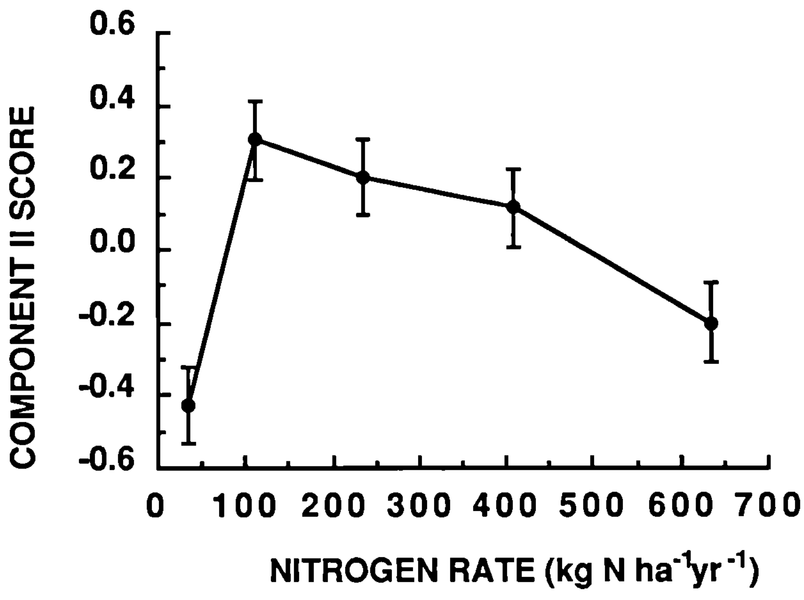

FIGURE 5.13

The effects of 5 rates of nitrogen fertiliser application on the mean of all three construction types on Component II score from the PCA of the ball impact data collected in 1992. Vertical bars represent SEs of the means presented.

of the soil constructions was significantly greater than those of the sand and USGA constructions. The mean scores for the sand, USGA and soil constructions were -0.75, -0.37 and 1.12 respectively, and the LSD ($p \leq 0.05$) was 0.42.

The main effect of the nitrogen fertiliser treatment on Component II scores is shown in Figure 5.13. Component II scores were very low at the lowest rate of nitrogen (35 kg N ha^{-1} yr^{-1}), rose sharply an N2 (110 kg N ha^{-1} yr^{-1}) and then gradually declined with increasing nitrogen rate.

CONSTRUCTION TYPE	PHOSPHATE TREATMENT ($kg\ ha^{-1}\ yr^{-1}$ P)	
	0	50
SAND	-1.17	0.26
USGA	-0.59	0.18
SOIL	0.65	0.68

TABLE 5.7
The effects of phosphate fertiliser on Component I scores on each of the construction types. LSD for comparing all the means presented was 0.51, and for means with the same construction, 0.36.

The correlations between the first two components of the PCA and total distance travelled by balls after impact, and measurements of hardness, shear strength, ground cover features and mean clipping yield (MCY) are shown in Table 5.8. Neither hardness or shear strength showed any significant correlation with Component I. This component showed positive correlation with total live cover, *Agrostis* spp. and *P. annua*, and negative correlation with *F. rubra* and the cover of dead material. Component II showed a positive correlation with shear strength, total live cover and *P. annua*. The total distance travelled after impact showed no correlations with the other features of the turf at $p \leq 0.005$.

These data show that Component I, increasing values of which indicated the tendency of impacting balls to create large pitch marks and screw back upon themselves, was associated with high amounts of live cover, the main components of which were *Agrostis* spp. and *P. annua* growing at a fast rate. Component II, which was related to the velocity of rebound, was associated with high total live cover in general and the cover of *P. annua* in particular. Shear strength measurements provided some indication of ball behaviour characteristics described by Component II.

MEASURE	Component I	Component II	Total distance
Hardness	-0.19	0.15	0.26
Shear strength	0.23	**0.43**	0.20
Total live cover	**0.45**	**0.36**	0.06
***Agrostis* spp. cover**	**0.29**	0.05	-0.19
***P. annua* cover**	**0.38**	**0.42**	0.27
***F.rubra* cover**	**-0.50**	-0.20	0.04
Dead material cover	**-0.28**	-0.16	0.04
MCY	**0.45**	0.08	-0.04

TABLE 5.8
Correlations between the first two components of the PCA analysis and the total distance travelled by balls after impact and other aspects of the turf. Values of the correlation coefficient (r) for $p \leq 0.05$, 0.01 and 0.001 are 0.195, 0.254 and 0.276 respectively. Correlations significant at $p \leq 0.001$ are shown in bold.

5.4 DISCUSSION

The treatment factors incorporated into the trial initiated a very wide range of responses in the turf of both a physical and biological nature. It is difficult to imagine however, how some physical distinctions, such as those between the construction types, might have influenced ball roll by means other than their influence on the turf species at the surface. The pronounced effects of the treatments on species composition, pattern and form, discussed in Chapter 4, and on growth rate as described above, were therefore mirrored by similarly pronounced treatment effects on ball roll.

Considering botanical composition, the data would imply that faster putting surfaces are characterised by a lower proportion of *Agrostis* spp. and a high proportion of *F. rubra* in the sward. This may be interpreted as a consequence of the different nature of the leaf surface of each species with which the ball interacts. Canaway & Baker (1992) found a similar effect using bowls, and Baker & Richards (1991) also found that fescue turf generally gives a faster putting surface than bent. This interpretation is complicated however by the fact that the cover of *F. rubra* was proportionately very low and also that it tended to be most abundant in low fertility sub-sub-plots on which total live cover was generally low. The greater proportion of low-lying litter and dead material also present in these plots presented a smoother, less cushioned surface to the ball which slowed it down to a lesser extent. The increase in ball roll at high nitrogen on the under-watered SWT constructions was almost certainly attributable chiefly to this feature of ground cover.

On the soil constructions, total live cover was always greater than 95 % but fertiliser nitrogen showed a marked effect on ball roll. The proportion of *P. annua* showed a simultaneous increase with nitrogen and the possibility that this species might present a slower surface in comparison with the *Agrostis* spp., which it tended to displace, may therefore not be discounted. However, the uniformity of the fertility response across all construction types does suggest that differential overall growth rates between swards were a major factor influencing ball roll. There was a distinct "reciprocal" similarity between the measurements of ball roll and those of clipping yield in the nature of the responses to all the treatments imposed. Colclough (1989) reported similarly reduced ball roll in response to nitrogen and phosphate fertiliser on fine turf before any significant changes in botanical composition were observed. Thus it would appear that the growth of turf in the time between mowing and play is governed to a great extent by climatic and fertility factors and may be suffiently rapid to affect putting speeds.

The observed responses of mean clipping yield to the treatment factors imposed are of interest and merit some discussion in themselves. On the sand and USGA constructions, the overall growth responses to nitrogen were clearly determined by the application or otherwise of phosphate fertiliser. Indeed, on the sand constructions in particular, it may be said that phosphate fertiliser application is absolutely essential for any significant upward growth to take place at all. By contrast, on the soil constructions, MCY response to nitrogen showed no dependence on phosphate whatsoever, and was apparently not limited even at the highest rate of nitrogen application. An effect of rootzone texture on effective fertility is therefore indicated. This form of response is consistent with the concept of phosphate buffering capacity (Wild 1988b) based on the clay mineral and organic matter content, which was discussed in Sections 1.7 and 4.4.

The total distance travelled by golf balls after impact, or the "holding power" (Colclough 1989), was chiefly affected by the construction type and the rate of irrigation. The response to irrigation treatment showed a similar form to that described for the soil moisture deficit in Chapter 3 (Table 3.2). Thus, as rootzones dried out in their respective characteristic ways, golf balls travelled further after impact. The soils however showed a higher water content (smaller SMD) than the SWT constructions but generally showed a greater total distance of travel after impact. This would indicate that rootzone water status alone cannot be used to indicate post-impact golf ball behaviour and that structural and textural aspects need to be considered.

Buchanan (1984) discussed the features which may affect the holding power of greens, and his basic tenet was that hardness is the main determinant of the outcome of impacts. This affects the ratio of rebound to incoming ball velocities or the coefficient of restitution (Daish 1972). Considering the treatment responses of hardness as measured with the Clegg Impact Soil Tester (CIST), their direction and magnitude certainly reflected the responses of total distance travelled after impact. The effects of nitrogen fertiliser on CIST measurements, though quite large, were not however reflected in the total distance response. Similarly, and perhaps in consequence, the correlation between hardness and total distance travelled was comparatively weak. This anomaly may be attributable to the actual level of hardness measured by the CIST and that actually relevant to the behaviour of the incoming ball. The 2.5 kg mass of the CIST hit the turf at a speed of about 2.4 m s^{-1}. The balls used in this study hit the turf at a speed of about 22 m s^{-1}. The respective rates of deceleration on impact were therefore of quite different orders of magnitude. At the speed of impact of the CIST decellerometer, the differential treatment effects on turf growth were therefore likely to be of greater significance in their effects on recorded hardness. The incoming balls, on the other hand, frequently penetrated the surface and interacted with deeper layers of the turf profile. Thus, rootzone texture and water status were found to be of greater significance with respect to the velocity of rebound. This would indicate that the CIST may be an inappropriate device for measuring hardness as it affects golf ball impacts, and one operating on the same principle but at greater velocities may be more informative.

The PCA analysis split the data set describing the behaviour of golf balls into two seemingly logical axes. Component I isolated features relating to spin retention at the end of the first bounce and indicated that this might be some function of the depth of pitchmark permitted by the green. Component II isolated those features pertaining to the velocity of rebound after impact and might be thought of as related to the coefficient of restitution. The sensitivity of Component I to all treatments indicated that spin retention is determined to a large extent by the "biological" features of the turf. These include botanical composition, growth rate and extent of live ground cover, all of which features correlated with Component I scores. Madison (1962) defined the amount of above ground growth of turf as "verdure". Component I could therefore be described as the verdure component of the turf. Similarly, factors pertaining to the "structural" aspects of the deeper layers of the turf profile affected Component II scores and these showed similar responses and significant correlation with shear strength measurements which bypassed the effects of verdure. The main effect of the lowest rate of nitrogen on Component II scores may have come about due to a lower root density associated with the very low total live cover. Further investigation would be necessary to establish the relationships between root density and the measures reported here.

The total distance travelled was a function of both components, but was more closely associated with Component II since, for the iron shot simulated in this study, the first bounce represented the largest proportion of the total distance travelled. If different golf ball flight criteria had been applied, for example, if a lower iron or driver - type shot had been simulated, the biological factors which influenced spin retention may have been of greater significance in determining the overall distance travelled after impact. The holding power of a green, and the expected outcome of impacts, may therefore be summarised in terms of component scores on each of the two axes. In order to estimate such scores, some measure of verdure could be used to establish the green status with respect to Component I, and a measure of hardness, derived from the decelleration of a measuring device projected at a velocity comparable to that of a golf ball in play, to establish the green status with respect to Component II. Such a method of summarising this aspect of the playing quality of a green would need to be tested alongside golf ball behaviour measuresments for a range of iron and driver shot simulations, but may ultimately provide a useful method of golf green classification and standardisation with respect to play.

CHAPTER 6 - THE QUALITY OF GOLF GREENS

6.1 INTRODUCTION

Establishing methods for the objective assessment of turfgrass visual quality has been the goal of many workers (eg Kamps 1969, Shildrick 1981, Bourgoin *et al.* 1985, Newell & Gooding 1990). However, the quality of a golf green is determined not only by its appearance but also by its quality of play and its capacity to provide a suitable surface throughout the year. Quality is therefore a multi-faceted feature.

The subjective assessment of turfgrass visual quality by simply asking people to score surfaces relative to one another can give an idea of what particular visible features are considered desirable. In the present study, such data may be analysed by ANOVA and statements may be made about the fertiliser and irrigation requirements of the best looking surfaces on each of the three construction types. Correlations between such assessments and objectively measured features such as ground cover, species composition and shoot density, may then indicate the objective measures pertaining most closely to the visual aspects of turf quality.

Techniques of measuring the red : far red ratio from plants provide data which bear a close correlation with visual merit (Birth & McVey 1968, Biran & Bushkin-Harav 1981, Gooding & Gamble 1990). Such measures are, however, subject to great variation over time. The actual values depend, for example, on the quality and intensity of sunshine at the time of assessment, and on the initial method of instrument calibration. No standard procedure of reflectance ratio measurement has, to date, been devised. The objective assessment of turfgrass colour on the other hand, using automatic colour meters, does provide a consistent statement of at least one aspect of turfgrass appearance which can be compared with other, isolated, measurements. The "L" (white - black), "a" (red - green) and "b" (yellow - blue) values obtained with a colour meter are internationally accepted as a standard means of assessing the colour of objects. Studies of turfgrass colour using such devices (eg Kavanagh *et al.* 1985, Kimura *et al.* 1989) therefore provide measures of one visual aspect of turfgrass quality which can be directly compared with data from totally unrelated sites.

The relationships between objective measures related to both the biology and the "mechanics" of turf, some of which have been described in previous chapters in terms of the influences of treatments upon them, and the overall quality of golf greens is by no means simple. For example, attempts to relate soil physical phenomena such as moisture content directly with post-impact golf ball behaviour are extremely difficult (see Chapter 5). The number of such objective measurements which could be carried out is open ended, and many correlations will exist within such measurements.

A classification of data from a survey of a large set of golf green surfaces, based on the correlations between measurements of differing aspects of quality, would enable workers to identify particular types, or classes, of greens. General characteristics pertaining to the quality of each class may then be described. Subsequently, a small number of observations of any green may be used to place that green into the most appropriate class. This having been done, statements about the quality of the surface, and hence how it compares with others, may be made on the basis of the characteristics associated with the class. Techniques for achieving such a classification are to be found in the field of multi-variate analysis.

Methods of classifying a large set of stands on the basis of sets of data from each one have been utilised to maximal value by the NCC for the classification of the vegetation types encountered in the British Isles (Anon. 1992a). Information from many different sites concerning the species composition and relative abundance was collated and analysed by a system which first arranged the sites in a matrix of inter-stand distances (or similarities). The matrix was then bi-sected according to its most natural line of separation, and the same procedure performed on the resulting two halves. This procedure was repeated until the desired size of classes was achieved. The resulting dichotomous dendrogram provided the framework for a key for the placing of new stands into a pre-determined class.

Classification of multivariate data sets is frequently carried out mathematically using one of the many techniques known as cluster analysis. For a review of these techniques, Jardine & Sibson (1971) provides a thorough mathematical treatment of the subject, and Everitt (1974) discusses the relative merits of differing approaches. If observations are taken on only two variables, the simplest, and arguably the best (Cormack 1971), way of finding natural groupings in a set of data is to plot the data on a scattergram and examine the graph visually. With more than two variables, principal components analysis (PCA) can be used to provide an effective reduction in dimensionality and scattergrams of the first and second principal components can be examined for clustering. If more than two components are needed to give a satisfactory representation of the data, then an algorithmic clustering of the scores on the appropriate number of components is called for.

Cluster analysis algorithms require the data to be expressed as a matrix of similarity coefficients between all possible pairs of stands. There are numerous such measures in use and they are usually defined to lie in the range 0 to 1. This can subsequently be expressed as a percentage. Chatfield & Collins (1980) discuss the differing coefficients and their relative merits. For the purposes described here however, the choice of similarity measure, and indeed of actual cluster analysis algorithm, is of limited significance provided a sensible classification is finally achieved.

The derivation of a dendrogram indicating the locations of suitably defined classes facilitates the generation of an artificial key based on the objective measures used. Stands not included in the original classification data set may therefore be placed in a class, using the key, provided the stand is located within the volume of the original similarity matrix. Clearly, if a classification is to be of value, the range of stand types needs to be large and to include representatives of extreme types. The objective assessments of the 180 sub-sub-plots of the trial certainly showed a wide range of results, as described in the preceding chapters. By classifying objective assessment data from the sub-sub-plots by PCA and cluster analysis, it was envisaged, in this study, that classes of turf could be identified on the basis of a limited number of objective assessments, and statements about the classes made in terms of their visual and playing quality and the management procedures associated with them. Direct correlations between perceived visual merit and objective assessments were also examined as a means of identifying the most direct indicators of visual merit from the range of objective assessments carried out.

6.2 MATERIALS AND METHODS

Visual merit

Visual merit evaluations of all sub-sub-plots were performed in 1991 and 1992. The close proximity of a golf course to the trial provided a supply of golfers prepared to score the 180 sub-sub-plots. Evaluators were asked "Please score the turf on the basis of how nice, in your view, it appears to be." Individuals with experience of turf management or assessment were not included because they would have biased opinions of what constituted good or bad appearance. For example, they may have had pre-conceived ideas of the relative merits of an individual species and their ability to recognise that species in the sward would influence their choice of merit score irrespective of the general appearance. In most cases, the wording of the request was clearly understood and did not raise any queries from the evaluators.

The WRCC - 11 turf committee adopted the use of a uniform 1 to 9 scale for visual assessments of turf quality (Horst *et al*. 1984), in which 9 represents the most desirable.

This system was used in this study. Evaluators were first asked to quickly examine each block and select a 9-score and a 1-score sub-sub-plot in order to familiarise themselves with the range. Like all other assessments, evaluations were carried out in rows across the trial from east to west in order to avoid confounding plot and sub-plot effects with temporal or human vacillation during data collection. The time taken by the evaluators to score the 180 sub-sub-plots was between 20 and 30 minutes, or between 7 and 10 seconds per sub-sub-plot.

In 1991, both golfers and non-golfers performed the evaluation in order to establish wether their respective opinions of turf quality differed. In order to improve the standardisation of the merit scores from different evaluators, the scores were converted to z-scores. ie

$$\text{z-score} = \frac{\text{sub-sub-plot score - mean score for the evaluator}}{\text{standard deviation}} \qquad (6.1)$$

In week 22 (May), 12 golfers (handicap < 25) and 9 non-golfers performed the assessment. Outliers were rejected by correlating individual evaluator z-scores with the overall mean for golfers or non-golfers. Evaluators giving correlation coefficients of less than 0.70 were rejected and the means recalculated. The grand mean of all the retained evaluators, pooling golfers and non golfers, was used to sort the 180 sub-sub-plots into a ranking order. The linear regressions against this series of the golfers and non-golfers were then compared. This showed no significant difference between the evaluation regressions of the two groups. In 1992, merit assessments were therefore carried out in weeks 15 (April), 23 (June) and 32 (August) by seven suitable evaluators and the mean scores over all assessments were analysed by ANOVA and used in subsequent comparisons.

Colour

Grass colour was assessed by taking a sample of the clippings from each sub-sub-plot mown at 5 mm in weeks 11 (April), 23 (June) and 31 (July) 1992. Samples were placed on a 9 cm diameter tray to a depth of 1 cm. The "L", "a" and "b" values of the clippings were then determined with a D25L - PC2 Delta Tristimulus Colorimeter System (Kirstol Ltd, Stalybridge) with a 95 cm viewing port. The "L" values denote the brightness, 100 describing pure white and 0 signifying black. Negative "a" values describe the intensity of greenness, the more highly negative the figure, the greener the grass. The more yellow the sample, the more positive the "b" value.

Classification

Principal components analysis (PCA) was performed on 12 objective measures, consisting of the total live cover (TLC - %), total cover of the sown species (*F. rubra* and *Agrostis* spp.) [SOW - %], cover of *P. annua* (POA - %) and shoot density adjusted for total live cover (see Chapter 4) [ADJ - /100 000 shoots m^{-2}]. These data were collected in October 1992. The mean of the three assessments of colour "L", "a" and "b" values were also included, as were the rootzone pH, phosphate (P_2O_5 - mg l^{-1} air dried rootzone medium), potassium (K_2O- mg l^{-1} air dried rootzone medium) content measured in October 1991, and the calcium content (Ca - mg l^{-1} air dried rootzone medium) measured in March 1991 and the organic matter content (OM - %) measured in March 1992. Subsequently used abbreviations and units are shown in brackets.

The first five principal components derived by the analysis accounted for 85 % of the variation in the data. The component scores for each sub-sub-plot on these axes were then used to derive a similarity matrix. The similarity measure (s_{ij}) used was the simplest of its kind and called "City Block", derived by the equation:

$$s_{ij} = 1 - \frac{|x_i - x_j|}{\text{range}} \tag{6.2}$$

in which x_i and x_j are the component scores of the *i*th and *j*th sub-sub-plots respectively.

The similarity matrix was then analysed by complete linkage cluster analysis. This is an agglomerative procedure which built up the hierarchical tree by grouping individuals into sets of increasingly disimilar clusters. The "distance" between two clusters was defined by this method as the disimilarity between their most remote pair of individuals. Groups of sub-sub-plots were selected by eye within the resulting hierarchical tree or dendrogram. The criteria used for their definition, or for "chopping the tree" at appropriate branches, were that about ten classes, with an average membership of 18 sub-sub-plots should be identified.

An artificial key to the classes

The mean values for the objective measures were calculated for each class. From this information, and the loadings of each measured variable on the first five principal components, a dichotomous key was prepared. This was aimed at placing a particular turf type into the appropriate class by means of a series of questions. The answers to these questions were based upon the objective measures recorded and indicated the class to which a particular surface belonged.

Overall quality evaluation

The mean values for each class of the visual merit rating, ball roll, and Components I and II from the impact study PCA described in Chapter 5 were calculated in order to provide an indication of the overall quality of each class in terms of both visual and playing characteristics. The construction type and irrigation and fertiliser regimes associated with each class were also assessed.

6.3 RESULTS

ANOVA of merit z - scores

The means of the merit z -scores collected in 1992 showed that evaluators were able to distinguish between treatment effects on turf of a high order of interaction. The effects of the nitrogen and phosphate fertiliser treatments on visual merit of the three construction types are shown in Figure 6.1.

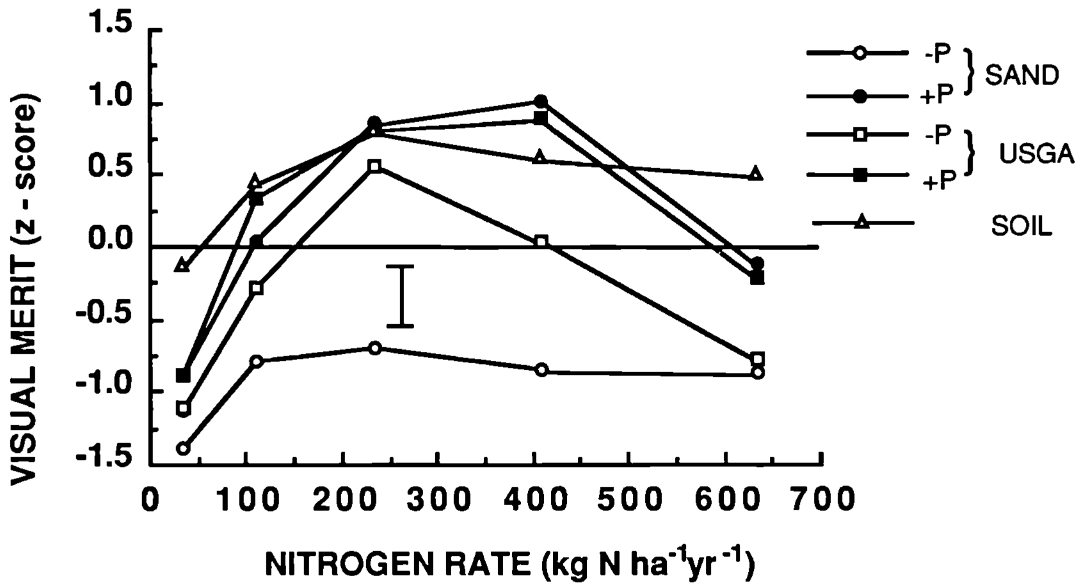

FIGURE 6.1

The effects of 5 rates of nitrogen application, with and without phosphate fertiliser, on mean visual merit of the three construction types in 1992. Phosphate fertiliser had no significant effect on the soil constructions, and so only the mean across the phosphate treatments are presented for this situation. Vertical bar represents LSD ($p \leq 0.05$) for all possible comparisons of the means presented.

Phosphate fertiliser had no significant effect on merit on the soil constructions and so the means shown for each nitrogen rate represent those across the phosphate fertiliser treatment for this construction type. On the sand constructions, visual merit was consistently the lowest when not treated with phosphate and showed very little response to nitrogen fertiliser. Sand and USGA sub-sub-plots treated with phosphate fertiliser both gave the highest merit ratings at a nitrogen fertiliser rate 410 kg N ha^{-1} yr^{-1}, and did not significantly differ at any rate of nitrogen. Merit scores increased with increasing rate of nitrogen and fell at the highest rate (635 kg N ha^{-1} yr^{-1}). The USGA constructions sub-sub-plots not treated with phosphate fertiliser showed a similar response to nitrogen as those treated with phosphate, but merit ratings were consistently lower and showed a maximum at a nitrogen rate of 235 kg N ha^{-1} yr^{-1}. On the soil constructions, maximum visual merit was reached at a nitrogen rate of 235 kg N ha^{-1} yr^{-1}. At rates above this, the soil construction visual merit declined only slightly and, at the highest rate of nitrogen, this construction gave the highest visual merit score of the three.

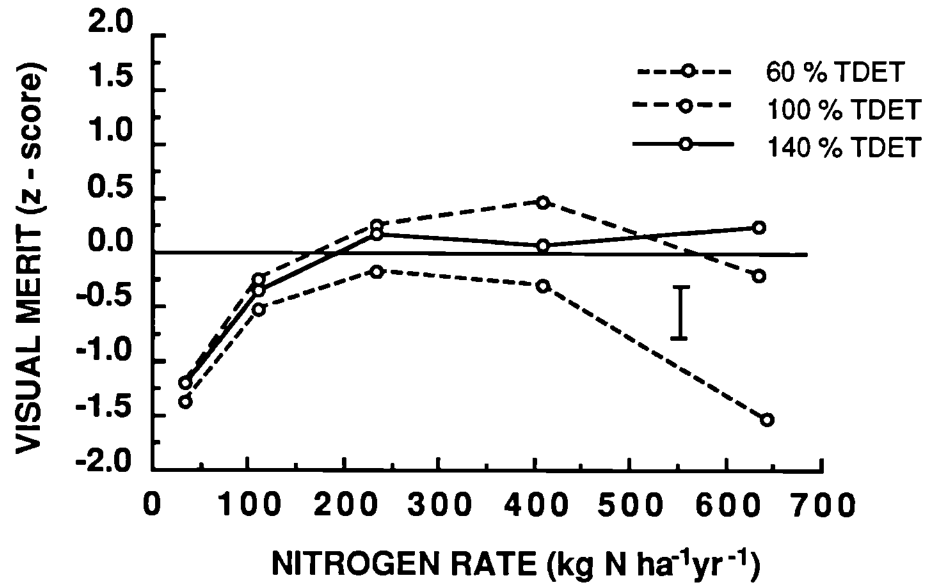

FIGURE 6.2

The effects of 5 rates of nitrogen application, at three rates of irrigation, on mean visual merit of the sand constructions in 1992. Vertical bar represents LSD ($p \leq 0.05$) for all possible comparisons of the means presented.

The lowest rate of irrigation produced a greater reduction in merit at the highest rate of nitrogen fertiliser on the sand construction types. This phenomenon occurred also, and to a greater extent, on the USGA constructions, on which the 100 % TDET irrigation rate also produced a slight reduction in merit at the highest rate of nitrogen. These results are shown in Figures 6.2 and 6.3 for the sand and USGA constructions respectively. This nitrogen/irrigation interaction was not observed on the soil constructions.

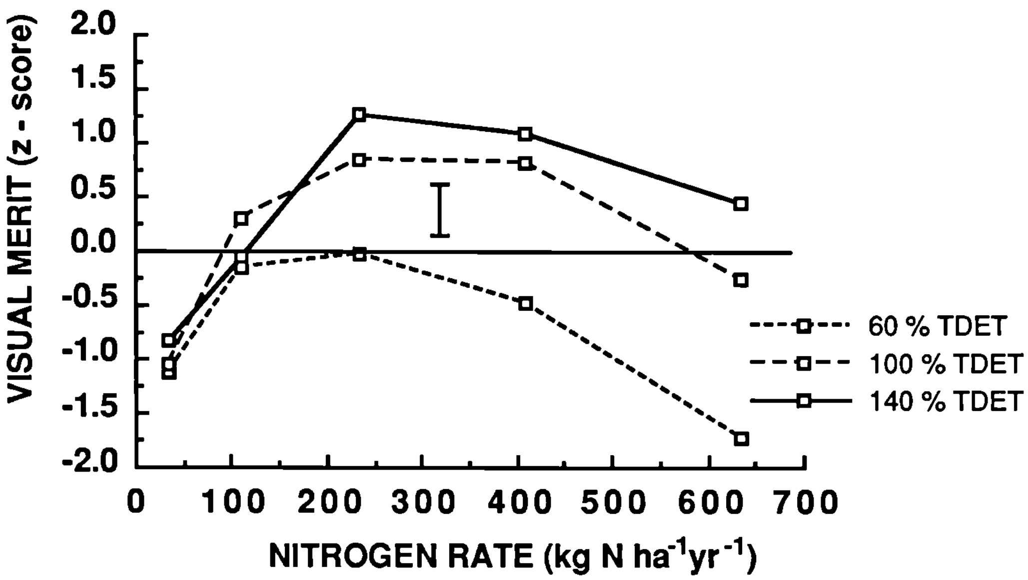

FIGURE 6.3
The effects of 5 rates of nitrogen application, at three rates of irrigation, on mean visual merit of the USGA constructions in 1992. Vertical bar represents LSD ($p \leq 0.05$) for all possible comparisons of the means presented.

OBJECTIVE MEASURE	CORRELATION COEFFICIENT WITH VISUAL MERIT - 1992
Total live cover (TLC)	0.83
Cover of sown species (SOW)	0.57
Cover of *P. annua* (POA)	0.24
Proportion of *P. annua* in TLC	0.10
Cover-adjusted shoot density (ADJ)	0.32
Colour meter "L"	0.20
Colour meter "a"	-0.29
Colour meter "b"	0.55

TABLE 6.1
Correlation coefficients between the means of objective assessments and subjective evaluations of visual merit carried out in 1992. Values for the correlation coefficient for $p \leq 0.05$, 0.01 and 0.001 are 0.195, 0.254 and 0.321 respectively.

Correlations between objective and subjective visual merit assessments
The correlation coefficients between the mean visual merit assessments for each sub-sub-plot for 1992 and the corresponding objective assessments of the visual aspects of the turf are shown in Table 6.1. An additional measure shown in the Table refers to the proportional contribution of *P. annua* to total live ground cover.

Total live cover showed the strongest positive correlation. The cover of the sown species (*F. rubra* and *Agrostis* spp.) showed positive correlation, and the correlations with *P. annua* as a whole and as a proportion of total live cover were weakly positive. The strongest correlation with the colour meter values was with the "b" value, indicating that a greater degree of yellowness was associated with merit by the viewers.

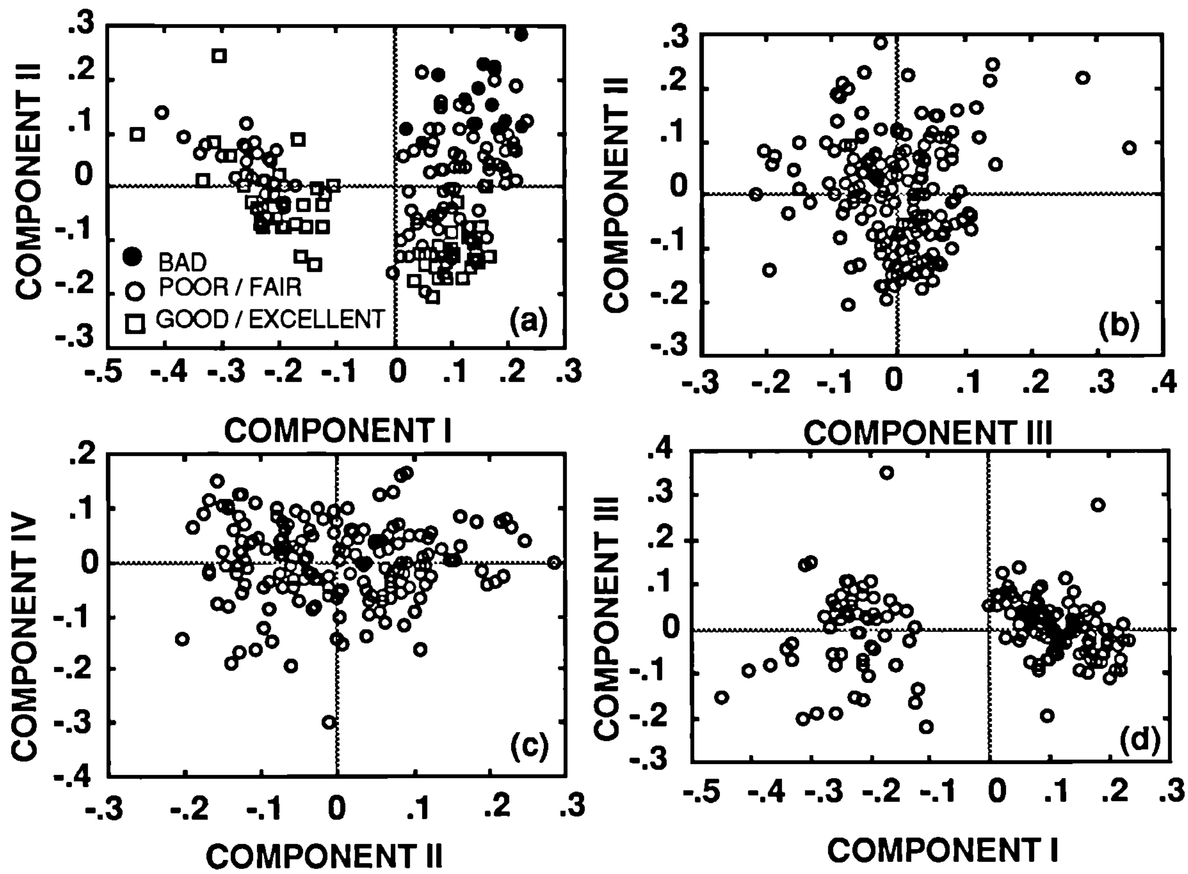

FIGURE 6.4

Scattergrams of Component I/Component II (a), Component III/Component IV (b), Component II/Component IV (c) and Component I/Component III (d) showing the distribution of the sub-sub-plots after PCA. Visual merit scores, grouped into excellent/good, fair/poor and bad classes are shown in (a).

Classification

In order to indicate the arrangement of the 180 sub-sub-plots in the multi-dimensional space defined by the similarity matrix, the scattergram displays of the component scores on some combinations of the first four principal components are shown in Figure 6.4. Figure 6.4a and 6.4d showed that a distinction between two major clusters occurred across Component I, and that any subsequent classification ought to take account of this division. No other distinctions of such clarity could be identified on a subjective basis. Superimposing some of the visual merit information obtained in 1992 onto the appropriate points in Figure 6.4a indicated that variations in perceived merit might show clusters within the two major goupings observed.

MEASURED	PRINCIPAL COMPONENT				
VARIABLE	I (45 %)	II (16 %)	III (9 %)	IV (8 %)	V (7 %)
TLC	-0.23	-0.54	0.01	0.13	0.21
SOW	0.07	-0.66	0.35	0.00	-0.01
POA	-0.33	0.17	-0.40	0.14	0.24
ADJ	-0.18	-0.25	-0.28	-0.56	0.26
"L"	-0.29	0.03	0.39	0.40	-0.02
"a"	0.03	0.31	0.60	-0.19	0.63
"b"	-0.36	-0.15	0.01	0.34	0.07
pH	-0.37	0.22	0.10	0.03	-0.03
P_2O_5	-0.26	0.10	0.19	-0.04	-0.56
K_2O	-0.26	-0.01	0.26	-0.57	-0.32
Ca	-0.41	0.05	-0.04	-0.05	0.07
OM	-0.39	0.00	-0.07	-0.13	0.08

TABLE 6.2

Latent vectors (or component loadings) of the 12 measured variables on the first 5 principal components. The percentages of the total variation accounted for by each component are shown in brackets.

The latent vectors, or component loadings, of each input variable in the PCA indicated the direction and extent with which each input variable was associated with each principal component. The loadings of the 12 input variables on the first five principal components which were used in the subsequent cluster analysis are shown in Table 6.2. The percentage of the total variation in the data accounted for by each component is also shown. Scores on component I increased with decreasing cover of *P. annua*, and decreasing pH, calcium and organic matter content. Scores on Component II increased with decreasing cover of the sown species (*F. rubra* and *Agrostis* spp.), and on Component III, scores increased with increasing colourmeter "a" values. Component IV scores increased with decreasing cover-adjusted shoot density and rootzone potassium content, and Component V scores increased with increasing colourmeter "a" values and decreasing rootzone phosphate levels.

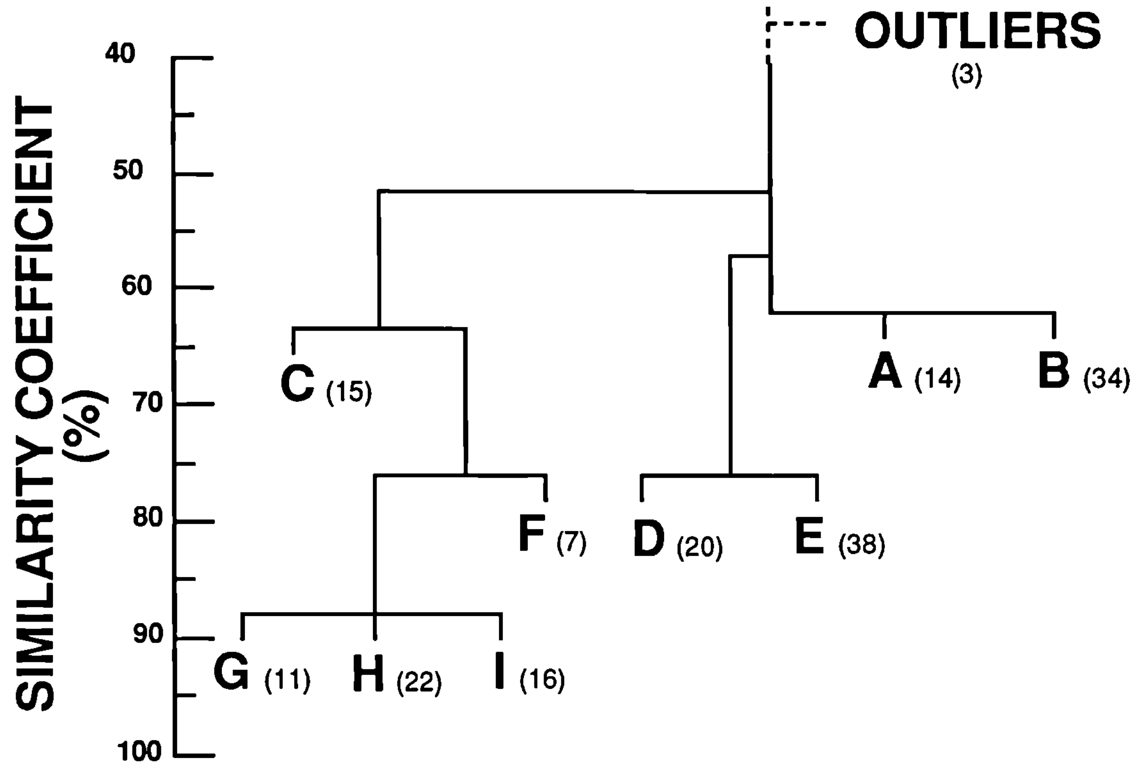

FIGURE 6.5

Dendrogram produced by complete link cluster analysis of the first 5 PCA axes. Numbers in brackets indicate the numbers of sub-sub-plots assigned to each group.

The complete link cluster analysis dendrogram divided the 177 sub-sub-plots into 9 classes (A to I) with 3 outlying sub-sub-plots, the classification of which was rejected. The resulting dendrogram is shown in Figure 6.5. Class membership ranged from 7, in Class F, to 38, in Class E. The positions of each of the clusters, or classes, in multi-dimensional space are shown in the PCA scattergrams in Figure 6.6. The axis pairings and their ranges correspond to the scattergrams indicating the entire data set in Figure 6.4. Classes were generally distinct, but consideration of position on several components was necessary before a particular surface could be assigned to a class. The major distinction occurring in the plane of Component I (Figure 6.4a and 6.4d) showed itself in the objective clustering procedure as the early separation of groups A, B and C. The membership of these groups comprised all of the left hand cluster of Figures 6.4a and 6.4d, although some members of Class C occurred in both of the major clusters.

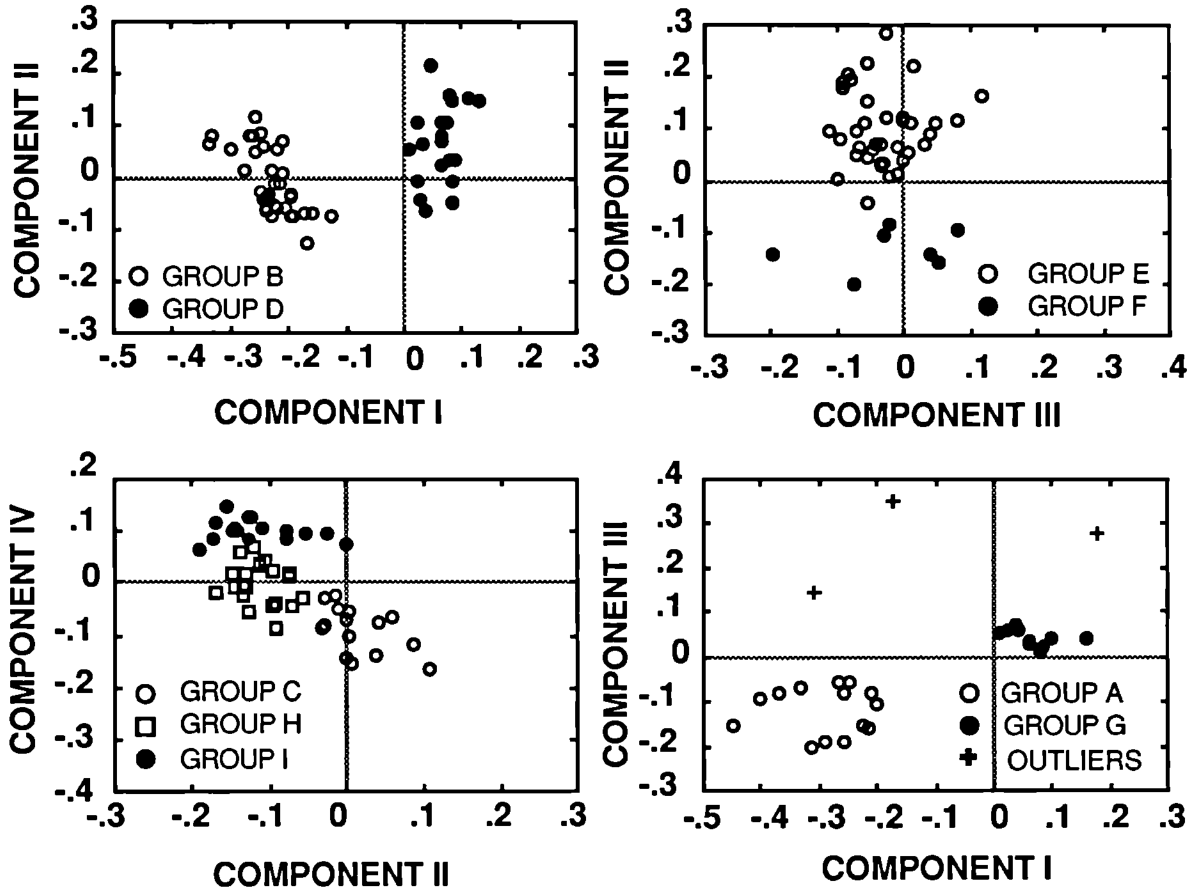

FIGURE 6.6

Scattergrams of Component I/Component II (a), Component III/Component IV (b), Component II/Component IV (c) and Component I/Component III (d) showing the distribution of the sub-sub-plots in classes A to I derived by complete link cluster analysis of the first 5 PCA axes (factors).

The mean values for each class of each of the 12 measured variables which were used to derive the PCA are shown in Tables 6.3 and 6.4. The standard errors are provided in parentheses. Table 6.3 gives the data for those measurements which pertained to the "visual" aspects of the turf. Table 6.4 gives the data for those measurements which pertained to the "chemical" nature of the rootzones.

CLASS	MEASURED VARIABLE						
	TLC	SOW	POA	ADJ	"L"	"-a"	"b"
A	98 (0.5)	30 (4.9)	68 (5.1)	1.1 (.06)	32 (.33)	9.3 (.15)	22 (.20)
B	88 (1.9)	66 (3.0)	22 (2.3)	1.0 (.04)	32 (.16)	8.2 (.10)	21 (.11)
C	72 (6.3)	50 (2.4)	22 (5.9)	1.2 (.07)	30 (.33)	7.8 (.28)	19 (.33)
D	56 (3.4)	55 (3.5)	1 (0.3)	0.6 (.04)	31 (.17)	7.1 (.20)	19 (.18)
E	44 (2.8)	42 (2.9)	3 (0.8)	0.6 (.04)	30 (.14)	7.6 (.16)	18 (.14)
F	89 (4.0)	86 (4.6)	3 (1.5)	1.7 (.14)	30 (.50)	8.1 (.38)	19 (.17)
G	86 (2.8)	85 (2.9)	<1 (0.6)	0.8 (.06)	31 (.15)	7.8 (.22)	19 (.27)
H	92 (1.4)	92 (1.5)	<1 (0.3)	0.8 (.05)	30 (.11)	8.5 (.13)	18 (.16)
I	89 (3.0)	87 (3.7)	2 (1.1)	0.7 (.05)	31 (.12)	9.5 (.13)	20 (.11)

TABLE 6.3

Mean (and SE) values of each of the "visual" measured variables for each of the 9 classes generated by the PCA/cluster analysis.

CLASS	MEASURED VARIABLE				
	pH	P_2O_5	K_2O	Ca	OM
A	6.7 (.12)	14 (1.8)	28 (3.3)	18 (.55)	3.8 (.08)
B	6.7 (.06)	14 (.62)	48 (2.9)	17 (.59)	3.9 (.04)
C	5.8 (.13)	7.2 (.62)	39 (3.5)	9.7 (1.8)	2.8 (.37)
D	5.5 (.08)	15 (.95)	30 (1.4)	1.0 (.14)	0.9 (.10)
E	5.3 (.04)	6.0 (.43)	21 (.69)	0.5 (.04)	0.8 (.08)
F	5.1 (.10)	12 (1.5)	36 (3.7)	2.9 (1.8)	1.5 (.43)
G	5.2 (.06)	10 (1.2)	30 (1.8)	1.1 (.18)	1.1 (.09)
H	5.0 (.04)	5.2 (.52)	25 (1.3)	0.9 (.12)	1.1 (.11)
I	5.1 (.06)	6.4 (.46)	18 (.96)	0.8 (.10)	0.8 (.10)

TABLE 6.4

Mean (and SE) values of each of the rootzone "chemical" measured variables for each of the 9 classes generated by the PCA/cluster analysis.

Artificial key to classes

From the information given in the dendrogram of Figure 6.2, Tables 6.3 and 6.4, and the component loadings given in Table 6.2, the "Artificial Key to Classes" shown below was derived. Qustions 1 and 2 related to the positions on Components I and II respectively. The remaining questions reflected a combination of the components.

KEY TO CLASSES

1 *P. annua* cover > 10 %, rootzone pH > 6.0, rootzone calcium content > 15 mg l^{-1} air dried rootzone (ADR), organic matter content > 3 %....Go to Question 3.
Not this collection of attributes....Go to Question 2.

2 Total live cover < 60 %, sown species contribution < 60 %....Go to Question 4.
Not this collection of attributes....Go to Question 5.

3 *P. annua* cover > 50 %, Colourmeter "a" values > 9, total live cover > 90 %, rootzone potassium content > 35 mg l^{-1} ADR....CLASS A.
P. annua cover < 50 %, Colourmeter "a" values < 9, rootzone potassium content < 35 mg l^{-1} ADR....CLASS B.

4 Rootzone phosphate content > 10 mg l^{-1} ADR....CLASS D.
Rootzone phosphate content < 10 mg l^{-1} ADR....CLASS E.

5 Total live cover < 80 %, *P. annua* cover > 10 %, organic matter content > 2 %, rootzone pH > 5.5, rootzone calcium content > 5 mg l^{-1} ADR....CLASS C.
Total live cover > 80 %, *P. annua* cover < 10 %, organic matter content < 2 %, rootzone pH < 5.5, rootzone calcium content < 5 mg l^{-1} ADR....Go to Question 6.

6 Cover adjusted shoot density > 100 000 shoots m^{-2}, rootzone phosphate content > 10 mg l^{-1} ADR material, rootzone calcium content > 2 mg l^{-1} ADR....CLASS F.
Cover adjusted shoot density < 100 000 shoots m^{-2}, rootzone phosphate content < 10 mg l^{-1} ADR material, rootzone calcium content < 2 mg l^{-1} ADR...Go to Question 7.

7 Colourmeter "a" values < 8, rootzone phosphate levels > 7 mg l^{-1} ADR....CLASS G.
"a" values > 8, rootzone phoshate levels < 7 mg l^{-1} ADR....Go to Question 8.

8 "a" values < 9, "b" values < 19, rootzone phosphate levels < 6 mg l^{-1} air dried rootzone....CLASS H.
"a" values > 9, "b" values > 19, rootzone phosphate levels > 6 mg l^{-1} air dried rootzone...CLASS I.

Surface quality

The mean scores for each class, expressed as a percentage of the observed range, of the visual merit ratings of 1992, ball roll from 1991, and position on the Components I and II derived from the impact study of 1992 described in Chapter 5 are shown in Table 6.5.

CLASS	VISUAL MERIT	BALL ROLL	COMPONENT I	COMPONENT II
A	64 (1.8)	18 (1.9)	70 (2.9)	63 (3.6)
B	59 (2.1)	37 (3.0)	46 (1.7)	64 (1.8)
C	46 (5.7)	46 (7.2)	44 (3.9)	48 (2.7)
D	27 (3.4)	78 (3.0)	30 (2.3)	38 (2.2)
E	25 (2.9)	48 (3.3)	38 (2.2)	35 (1.8)
F	58 (5.7)	35 (5.3)	48 (4.7)	40 (2.9)
G	52 (6.5)	44 (3.5)	34 (3.0)	47 (3.6)
H	66 (3.5)	21 (2.2)	42 (2.4)	44 (2.1)
I	72 (4.1)	20 (3.1)	67 (2.9)	44 (2.5)

TABLE 6.5

Mean scores for each class (percentage of observed range) of visual merit ratings 1992, ball roll 1991, and position on the Components I and II derived from the impact study of 1992 .

Characteristics of the classes

Given that the treatments received were known for each member of each class, the classes were described individually in terms of their overall visual and playing quality and the management procedures whereby the respective surfaces came about. By converting the ball roll data to Stimpmeter green speeds (Equation 5.2), the classification of speeds by Radko (1977) allowed the ball roll characteristics to be expressed in Radko's terminology of slow, medium/slow, medium, medium/fast and fast for regular and tournament play.

CLASS DESCRIPTIONS

CLASS A: Visually good. Regular play - medium, tournaments - very slow. Iron shots show good spin retention but rebound at high speed. All soil constructions. Mean nitrogen rate - 540 kg N ha^{-1} yr^{-1}.

CLASS B: Visually fair to good. Regular play - medium, tournaments - slow. Iron shots show medium spin retention and rebound at high speed. All soil constructions. Mean nitrogen rate - 153 kg N ha^{-1} yr^{-1}.

CLASS C: Very variable. Visually poor. Regular play - medium, tournament - slow. Post-impact ball behaviour too variable for general statements. 60% soil construction, 33% USGA. Mean nitrogen rate - 247 kg N ha^{-1} yr^{-1}. 80% received no phosphate.

CLASS D: Visually poor. Regular play - medium/fast, tournament - medium/slow. Iron shots show poor spin retention and low rebound velocities. 60% - pure sand, 40% - USGA. Mean nitrogen rate - 50 kg N ha^{-1} yr^{-1}. 80% received phosphate.

CLASS E: Visually very poor. Regular play - medium, tournament play - slow. Iron shots show poor spin retention and rebound at low velocities. 71% - sand, 29% - USGA. Mean nitrogen rate - 393 kg N ha^{-1} yr^{-1}. 13 % received phosphate.

CLASS F: Visually fair. Regular play - medium, tournament play - slow. Iron shots very variable but rebound velocities fairly low. 71% - USGA, 29% both sand and soil. Mean nitrogen rate - 238 kg N ha^{-1} yr^{-1}. Phosphate applied to all.

CLASS G: Visually fair. Regular play - medium, tournament play - slow. Iron shots show medium spin retention and rebound velocity. 73% - USGA, 27% - sand. Mean nitrogen rate - 180 kg N ha^{-1} yr^{-1}.

CLASS H: Visually good. Regular play - medium, tournament play - slow. Iron shots show medium spin retention and rebound velocity. 68% - USGA, 32% - sand. Mean nitrogen rate - 180 kg N ha^{-1} yr^{-1}. 50 % received phosphate.

CLASS I: Visually excellent. The slowest putting speeds of the trial. Regular play - medium, tournament - very slow. Iron shots show good spin retention and medium rebound velocities. 50% - sand, 50% - USGA . Mean nitrogen rate - 382 kg N ha^{-1} yr^{-1}. 94 % received phosphate. 80 % received irrigation above ET demand.

6.4 DISCUSSION

On the basis of the visual merit evaluations only, recommendations for the optimum nitrogen fertiliser regimes for each construction type could be drawn up by fitting curves to the merit response data and establishing the rates at which maximum visual merit would be obtained. The shapes of these responses indicted at first that inverse polynomial curves might be appropriate. These were used successfully by Canaway (1985a,b) for the establishment of the appropriate nitrogen fertiliser rate for maximising ground cover of *Lolium perenne* football turf. It was found however that the rapid fall-off in visual merit which took place on the SWT constructions at the highest rate of nitrogen detracted from the accurate fitting of such curves.

By imagining free-hand curves fitted to the merit response data, it is possible to say that optimum nitrogen rates for both SWT constructions lay between 350 and 400 kg N ha^{-1} yr^{-1} when phosphate fertiliser was applied, and around 240 kg N ha^{-1} yr^{-1} on the USGA constructions when no phosphate fertiliser was applied. These observations represent optimum rates which are slightly higher than those reported by Lawson (1987) who found that optimum nitrogen rates for *Festuca / Agrostis* turf grown on pure sand lay between 200 and 400 kg N ha^{-1} yr^{-1}. On sand constructions, the application of phosphate fertiliser would appear to be absolutely essential. On the soil constructions, nitrogen fertiliser rates of between 200 and 400 kg N ha^{-1} yr^{-1} produced the best looking surfaces in 1992, and the application of phosphate fertiliser was not necessary. On both SWT constructions, the data indicated that the application of decreasing amounts of irrigation lowered the optimum nitrogen fertiliser input rates. These complementary effects of irrigation and nitrogen fertiliser agree with the findings of Madison (1962) and Mantell (1966) referring to the growth of turf consisting of pure stands of *A. capillaris* and Kikuyugrass (*Pennisetum clandestinum*) respectively.

The results indicated that, of the range of objective measurements carried out, the assessment of total live cover by means of a point quadrat (Laycock & Canaway 1980) provided the most closely correlating objective measure pertaining to the perceived visual quality of mixed species golf green turf. The relative contribution of *P. annua* to the swards did not greatly affect perceived merit. The range of variation in total live cover over the trial was however very large (Chapter 4), and many of the swards were consequently not representative of golf green surfaces. Since evaluators were asked to score sub-sub-plots for merit within a range determined by the trial itself, the results highlighted the importance of total live cover but, in doing so, may have obscured the likely influence of more subtle factors such as shoot density. This has been associated with visual merit in mono-culture situations (Gooding & Newell 1991). Similarly, the apparent preference for colour meter yellowness may simply have described the abundance of the lighter coloured *P. annua* on the soil constructions (see Chapter 4) which constituted 33 % of the total number of sub-sub-plots, had generally high total live cover and consequently acquired high merit ratings. The possible influences of differing species composition effects on perceived merit might therefore have been obscured.

The evaluation of colour was independent of the percentage ground cover and reflected the colour of the actual grass present. In theory, these assessments, coupled with statements of total live cover, might account for a great deal of the variation in perceived visual merit. The fact that more than one species contributed to the total live cover and colour assessments complicated this however. If an experiment were conducted in which total live cover (and all other factors) were kept constant, but the relative contributions of different species to the swards were varied, the relationships between perceived merit and the objective measures of clipping colour and sward composition could, to some extent, be elucidated. Objective assessment of turfgrass visual merit could then be conducted on the basis of measurements of total live cover, the relative contributions of individual species and the colour of clipping as measured with a colour meter. The possible use of other measures of turfgrass performance, such as shoot density and leaf width, which have been of value in single species situations (Brede & Duich 1982, Turgeon 1985, Gooding & Newell 1991), probably demands further investigation before application to mixed species sward evaluation.

The presentation of the visual merit ratings of each of the derived classes alongside the corresponding ball roll and impact evaluations highlighted the point that good visual and playing quality generally demand contrasting surfaces. Thus, for example, the fastest greens were among the least attractive surfaces and *vice-versa.* However, the slower speeds associated with the desirable feature of increased growth might be improved by increased frequency and/or decreased cutting height. An actively growing, more vigorous sward should be able to tolerate such conditions. The variations observed within the classes with respect to the post - impact ball behaviour reflected the variability of the original data, in addition to the limitations of the classification procedure discussed below. But major differences in both visual and playing quality responses were identified by the classification, despite these measurements not being included in the derivation of the classes. This testifies to the potential of the method as a means of classifying golf greens on the basis of overall quality on a wider basis.

The early separation of the soil construction classes, A and B, reflected the great differences in performance between these and the suspended water table constructions (SWT) which the data presented in ANOVA form in previous chapters demonstrated. However, on the basis of a visual analysis, clustering within the two "clumps" separated along Component I of the cluster PCA was not very distinct. This may imply that these points represented locations in a continuum of variability in which no natural groupings actually occurred. This is theoretically possible given, for example, that the nitrogen fertiliser treatment was applied at five progressively increasing rates. Similarly, in

Chapter 4 the concept of descriptions of the surfaces representing a momentary state during a gradual directional change in condition was put forward. In this respect, the positions of the sub-sub-plots within the similarity matrix may intrinsically vary with time, and may show a continual trend with time as they might have done in response to nitrogen fertiliser. Such a continuum of variability would imply that, beyond the clear separation of groups A and B, the identification of further classes was purely artificial. This is a familiar debate discussed, with reference to the classification of plant communities, by Gauch (1982). The continuum concept would certainly explain the variability observed within the classes with respect to both the objective and subjective variables measured.

While recognising the likely drawbacks of the classification procedure, the mathematical method used was successful in producing a classification of the surfaces. The set of classes of surface, isolated from the similarity matrix by the cluster analysis, appeared to be logical and therefore could possibly have been identified subjectively, rather than by the chosen algorithm, were this practicable. The key to the classes could be used to classify any one of the 177 sub-sub-plots which generated the classification if the user were provided with the appropriate objective measures. The obvious limitation is however that greens not included in the original classification may not "fit" into a class because their particular range of objectively measured characteristics were not encompassed within that of the original similarity matrix. For example, it is quite possible for a pure sand golf green to have a pH of more than 6.0, but an organic matter content considerably less than 3 %. Such a surface could not get past question 1 in the Key to Classes. This limitation was anticipated and highlights the need to sample a wide range, and much larger set, of greens in order to derive the initial classification before the technique could be utilised as a viable means of golf green classification.

If a wider range of soil types were sampled, the distinction between the soil and the SWT construction types would probably be filled in by turf on soils with intermediate soil chemical and physical properties. Considering the Key to Classes, the placing of a green into a class relied on both physico-chemical and visual assessments. If a classification were to be made which encompassed a wider range of soil types, it could be anticipated that further objective measures, summarising differences in soil texture, structure, depth, infiltration rate and so on, all features which may affect one or more aspects of overall quality, would be necessary in order to accurately locate greens within a similarity matrix and a subsequent classification. Also, seasonal variation in the measured parameters would need to be taken into account by taking more than one assessment per year for each site. Like the classification of the vegetation of the British Isles (Anon 1992a), a practicable classification scheme for golf greens would require an initial survey of greens in which many objective tests were carried out as well as assessments of playing qualityand perceived merit. The data set must also encompass as large and wide-ranging a set of greens as possible. The initial labour requirements for the establishment of such a system of golf green classification would be great, but the methodology has been shown to work and the benefits for the sport would be considerable.

CHAPTER 7 - FINAL DISCUSSION AND CONCLUSIONS

7.1 INTRODUCTION

One of the major objectives of the research, outlined in Section 1.10, was to illustrate how different fields of scientific work may be drawn upon in studies of golf green maintenance. Concepts from the fields of soil physics, grassland ecology, ballistics and multivariate analysis were applied to investigate the relevant aspects of golf green science. In this wider context, this thesis represents little more than a general overview of the subject.

The nature of empirical research is such that explanations for observations cannot be provided, but hypotheses may be generated which may subsequently be tested. Since much of the work described was empirical, few definite conclusions could be made, but the directions which further research might take were indicated. In this chapter, conclusions derived in the body of the thesis are summarised, and some areas of further research are suggested.

7.2 WATER AND THE GOLF GREEN

Much research has been carried out to establish the differing evapotranspiration (ET) rates of turfgrass cultivars and species (see Section 1.4). Techniques for ET measurement are therefore quite refined and the methods employed in this study could have been improved considerably were this the sole objective. It would appear that models for predicting turfgrass ET from meteorolgical data on the basis of Penman's original studies (Penman 1948, 1963) can provide a reasonable degree of accuracy. Such models may therefore be utilised to form the basis of irrigation management schedules. However, the study also demonstrated that accurate estimation of ET loss represents only a part of the effective use of irrigation in golf green maintenance. Major consideration must be given to the construction type and the nature of the rootzone medium.

In turf science a great deal has been made of the relationships between particle size distribution, or mechanical analysis, infiltration rates and moisture retention. While such relationships clearly exist (see for example Schmidt 1980), this study demonstrated their complex nature, and highlighted the need to consider the influence of structural as well as textural aspects of soils. The measurements of porosity, and pore size distribution revealed differences between all three construction types, responded to wear treatments over time, and showed proportional variation with infiltration rates and moisture deficits. A refined assessment of soil structure may therefore be of greater practical value in determining irrigation and other management requirements than mechanical analysis. Turfgrass experiments aimed specifically at illucidating the relationships between these factors would be of immense value.

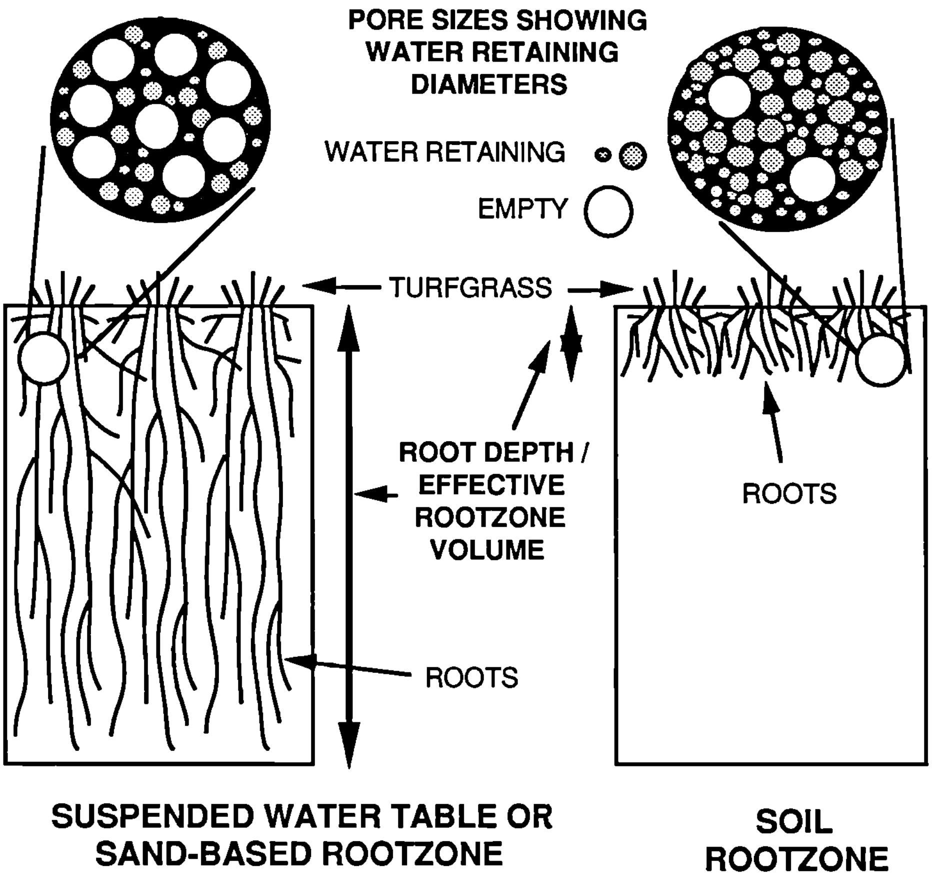

FIGURE 7.1

Schematic cross sections of a SWT or sand based rootzone (left) and a soil rootzone (right) showing deep and shallow rooting on each respectively. The insets show how, with the same total porosity, the larger proportions of small pores on the soil can increase water retention with respect to the SWT constructions. The SWT construction type is able to compensate for this by having a greater root depth.

One important feature which was not examined in this study was root depth. However, a brief examination of the three rootzones revealed that, at the end of the trial period, roots had ramified throughout the rootzones and extended even into the blinding layer of the SWT constructions, but reached a depth of only about 100 mm on the soil constructions (unless the roots had grown down the hole created by a verti-drain tine). It was observed that turfgrass quality was largely unaffected by the development of significant moisture deficits within the rootzones, and that the water retention capacity of the SWT rootzones was considerably less than that of the soil constructions at tensions below field capacity. Therefore, it may be hypothesised that moisture availability was generally adequate because the effective rootzone volume was enhanced on the SWT constructions, and because the available water content of the upper layers of the soil constructions was greater. This hypothesis is illustrated in Figure 7.1.

To some extent the rate of infiltration may represent the ease with which deeper areas of the rootzone may be replenished with water. The SWT constructions, which had high infiltration rates and deeper rooting, may therefore be able to accommodate infrequent, heavy irrigation treatments (replacing accumulated ET losses). The soil constructions on the other hand, with low infiltration rates and shallower rooting, may be better suited to frequent, light irrigation, which it did in fact receive.

The frequency of irrigation is of great importance. A widely held belief is that a "little and often" approach is best, but this has been criticised for encouraging shallow, and consequently drought intolerant, rooting and the enhanced encroachment of *P. annua* on the permanently moist surface. The alternative is less frequent, greater irrigation applications, aimed at rapidly reducing moisture deficits when a critical point is reached. With this approach, conflict may arise between the biological needs of the turf, and the desires of golfers to play on moist surfaces which "hold" the ball.

On the basis of this study, it may be concluded that optimum irrigation frequency is a function of the structure and infiltration rate of the rootzone, and the amount of water necessary is a function of ET. Unfortunately, the experimental treatments employed provided little information regarding the relationships between drought tolerance, irrigation frequency and construction or rootzone type. This highlights the need to target research pojects more specifically towards these goals.

7.3 FERTILISER USE ON GOLF GREENS

From a turf management perspective, a number of observations regarding the effects of nitrogen and phosphate fertiliser may be of significance. Maximising live cover was found to be of great importance with regard to turf quality. In order to maintain maximum live cover on soil constructions, a minimum nitrogen fertiliser input rate of 235 kg N ha^{-1} yr^{-1} was appropriate. On the USGA constructions the same minimum rate of nitrogen was suitable, but the application of phosphate was necessary to obtain maximum benefit. On the pure sand constructions maximum ground cover was achieved at nitrogen input rates of between 235 and 410 kg N ha^{-1} yr^{-1} and the application of phosphate fertiliser was essential.

These values reinforce the results of much previous work (Section 1.6). It is important to note that the number of applications of nitrogen fertiliser differed for each construction type (Section 2.9). If the soil constructions had received the nitrogen treatment in nine dressings per year, as did the sand constructions, the sward composition may have been different.

The necessity, or otherwise, for the application of phosphate fertiliser to fine turf would appear to hinge on both the levels of phosphate measured in soil extracts and on the texture of the rootzone media itself. Serious consideration should therefore be given to the quantities of clay minerals and organic matter present. In this respect, mechanical analysis will clearly be of importance. The effects of phosphate fertiliser on *P. annua* ingress were not fully explored by this study. However, as with the effects on overall turf quality, the influence of phosphate on *P. annua* is likely to be similarly dependent on rootzone texture.

The maintenance of stable and appreciable quantities of *F. rubra* in the swards on the construction types examined would appear to be beyond the capacity of the particular management factors under examination to achieve. There was a good deal of evidence to suggest that the development, or otherwise, of *P. annua* in golf green turf was highly dependent on the capacity of the rootzone to facilitate the successful germination and establishment of the seeds of the species, whilst subsequent growth and development rate was influenced by general fertility factors.

From an aesthetic point of view, the trial surfaces of the "finest" appearance were the USGA constructions receiving 410 kg N ha^{-1} yr^{-1}, 50 kg P_2O_5 ha^{-1} yr^{-1}, and the highest rate of irrigation (140 % TDET). On the sand constructions, maximum visual quality was maintained at similar nitrogen and phosphate fertiliser rates, but no difference between the 140% and 100% TDET surfaces was observed. On the soil constructions maximum visual quality was maintained over the 235 - 410 kg N ha^{-1} yr^{-1} rates and was unaffected by the phosphate and irrigation treatments.

7.4 IMPLICATIONS FOR THE GAME

This study highlighted the complexity of the relationships between putting speed and management factors. One of the most important observations was that speed was inversely related to turf growth rate. Since vigorous growth was also associated with enhanced visual merit, it is clear that a compromise between these two features of overall quality has to be reached. The ability of actively growing swards to tolerate closer mowing may be one means of achieving such a compromise.

The techniques developed for assessing the post-impact behaviour of golf balls were reasonably successful. The length and height of the immediate bounce after impact was found to be a function of the physical nature and water content of the rootzone media, and the capacity of retained spin to hold balls in the subsequent roll phase was affected by the "lushness" of the turf. A series of experiments in which rootzone water content, structure and texture were varied and monitored would shed more light on the complex relationships between soil type and golf ball behaviour. It is likely that, at this stage, an empirical approach to such experiments is most suitable, because the inter-relationships between all the possible variables involved when spinning golf balls collide with turf are so complex and poorly understood.

Defining the optimum state in which both the vigour of the turf and the quality of play are maximised is extremely difficult. This difficulty is confounded to some extent by the lack of any generally accepted "standards" of playing surface. Thus, what constitutes healthy turf may be fairly easily identified, but there have been no studies, to date, investigating what golfers actually consider to be a good surface. They are likely to have widely different views on this subject. A good deal of animosity between greenkeepers and golfers (who generally constitute the greens committees) might be avoided if standards of playing quality could be formally defined.

7.5 THE CLASSIFICATION OF GOLF GREEN QUALITY

The multi-faceted nature of the quality of golf greens is such that to attempt to place a particular green on a single scale of overall performance is unwise. Nor is the situation one of "horses for courses", in which a particular type of green may be identified as being "best" for a particular situation. The problem lies with the fact that golfers generally have differing views on what constitutes a good or a bad green. This is perfectly acceptable, given that the ultimate objective of golf green management is to enhance the pleasure of playing golf.

Separating overall quality into visual and playing components, and the latter further into putting and impact performance, was shown to be a realistic breakdown of what is understood by golf green quality. This allowed the quality of greens to be expressed in each of the component terms, without specifying an ultimate form of green. In theory, this approach should offend nobody.

Having identified the components of quality, the objective measures which most closely corresponded with the perceived merit in each case may be used to eliminate the need for consulting golfers for their subjective opinions. This represents a step towards being able to classify the performance standard of any one green on the basis of a few objective tests. However, the classification method examined in this study went further and attempted to define the quality of greens on the basis of semi-permanent features of the turf which were unlikely to vary greatly over the year or in response to differing weather conditions.

This procedure was successful to some extent, but was severely limited by the small number of objective assessments which were used in the analysis. Additional measures should have been included, chosen to summarise differences in, for example, soil texture, structure and infiltration rate. These features were shown to affect at least some aspects of quality.

A practicable classification scheme for golf greens would therefore require an initial survey of greens in which many objective tests were carried out as well as assessments of playing quality and perceived merit. The success or otherwise of such a scheme would be dependent largely upon the relevance to overall quality of the chosen objective measures.

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