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Use of vegetation in civil engineering

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IMPORTANT NOTICE

This book is a reprint of the edition published in 1990 and reflects best practice at that time. It also contains contact details for a large number of organisations which have not been updated. The names, locations and structure of many of these organisations will have changed.

Additionally, government reorganisation has meant that responsibilities have been moved variously between government departments. References made to government agencies in this publication should be read in this context. For clarification, readers should contact the relevant agency.

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The CIRIA project drew together information from a review of published technical literature; a survey of and discussions with UK practitioners, researchers and organisations involved with bio-engineering; a limited number of site inspections; discussions/correspondence with key European and US experts; and the experience of the authors and the Steering Group.

Responsibilities for liaison with other organisations:
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The project was carried out with the guidance and assistance of the Steering Group listed below:

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L A Boorman	Institute of Terrestrial Ecology
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[2] International Trade Centre UNCTAD/GATT
[3] Institution of Civil Engineers, Ground Engineering Group Board
[4] British Association of Landscape Industries (BALI)

Contents

Glossary

Amenity (vegetation)	Not grown as a commercial or edible crop
Biomass	The total mass of living and dead biological material
Community (plant)	Particular assemblage of plant species reflecting the prevailing environment, soil type and management
Cultivar	Cultivated variety of a plant species, usually bred from a wild “ecotype”
DIN standards	West German standards similar to those of BSI
Ecotype	Naturally occurring variant of a species which is adapted to a particular set of ecological or environmental conditions
Establishment period	1) Time between sowing of the seed and the stage at which the plant is no longer reliant on the nutrient supply in the seed. 2) Time between planting and the stage at which special care is not required to ensure that all parts of the plant are functioning normally.
Eutrophication	Nutrient enrichment of a habitat by natural or artificial means; leads to dense and uncontrolled vegetation growth
Evapotranspiration	Moisture loss from a vegetated ground surface due to transpiration via the leaf and evaporation from the vegetation and soil surfaces
Geotextile	Synthetic or natural permeable fabric used in conjunction with soil and vegetation; principally for erosion control, filtration, soil reinforcement and drainage
Grass	Member of a distinct botanical family, widely utilised by man; includes rushes, sedges and reeds; non-woody usually short-lived individuals which can withstand grazing and trampling
Growth habit	The physical form and geometry of a plant
Herb	Generally non-woody flowering plant; no specific definition but covers a very wide variety of small plants; excludes grasses but merges into shrubs
Humus	Organic fraction in the soil, decomposed plant (and animal) material
Hydroseeding	The rapid application of seeds and fertilisers in a water suspension onto an area where, for reasons of access, speed of application or ground condition, conventional techniques cannot be used

Litter layer	Layer of undecomposed plant debris on the soil surface
Management (of vegetation)	The control of vegetation for a specific purpose, to achieve a required growth habit or to manipulate the plant community
Metabolic activity	The internal biochemical processes which are necessary for plant growth and function
Monoculture	Artificial plant community (sown or planted) which is composed of a single species
Mulch	Layer of synthetic or natural material applied to the soil surface primarily to conserve moisture or suppress herbaceous growth
Nurse species	Plant species which are included in a sown or planted mixture, to shelter the slower growing components or to provide some quick protective growth; usually lasting only a short time before being superseded by long-term components
Nutrient harvesting	The control (reduction) of nutrient levels in the soil by the regularly cutting and removal of the vegetation cover
Parent material	The original sediment or rock from which a soil is formed by weathering
Pioneer species	Those species which are particularly well-adapted to be the first to colonise bare ground
Poaching (soil)	Damage caused to soil as a result of trampling by livestock or machinery in wet conditions
Propagation	Multiplication and establishment of plant material using seeds, cuttings, offshoots, etc
Reinforced soil	The inclusion in a soil mass of layers of metallic, synthetic or natural materials to facilitate construction of steep slopes and retaining structures
Rhizome	Stem growth which creeps beneath the soil surface, rooting at nodes to form new individuals; found in many grasses and herbs
Seed bank	The store of dormant seed in the soil
Shrub	Woody plant of substantial stature, smaller than a tree but some overlap with this group
Soil horizon	Layer or zone within the surface soil formed by natural processes of weathering, humus accumulation and plant/ animal activity; usually distinguished as topsoil and subsoil
Stolon	Stem growth which creeps over the ground surface, rooting at nodes to form new individuals; found in any grasses and herbs

Succession	Natural sequence or evolution of plant communities, each stage dependent on the preceding one, and on environmental and management factors
Sucker	Root (or stem) growth which eventually separates from the parent plant and forms a new individual
Tiller	Specific to grasses; a shoot branching from the base of an existing grass plant; will form clumps or spreading mats depending on the growth habit
Tree	Woody plant of large (generally >3 m) stature

Notation

A	Area of soil under consideration; leaf area per unit volume
A^C	Air capacity of soil
b	Transverse width of crown of tree in windthrow analysis; width of slice in slope stability analysis
c	Apparent soil cohesion
c'	Effective soil cohesion
C	Crop and soil conservation factor; Rational runoff coefficient; Penman root constant
C_D	Drag coefficient; bulk drag coefficient
C_d	Vegetation drag coefficient
c_R	Increase in soil cohesion due to root reinforcement
c'_R	Increase in effective soil cohesion due to root reinforcement
c_s	Increase in soil cohesion from soil suction due to evapotranspiration
c'_s	Increase in effective soil cohesion due to evapotranspiration
CI	Vegetation retardance index
d	Thickness of rooted zone in segment of slope; average stalk diameter; shear stress from windblow
e	Void ratio
E_a	Actual evapotranspiration losses arising from ground surfaces covered with vegetation
E_o	Equivalent evaporation arising from an open water surface
E_t	Potential evapotranspiration losses from ground covered with standard reference vegetation (usually a grass sward)
H	Height of shelterbelt; thickness of soil and decomposed rock mantle
I	Intensity of erosive rain; soil erodibility by wind
L	Moment arm of centroid of vegetation within critical slip circle about centre of rotation; distance to flow re-attachment point downstream of shelterbelt barrier
L_d	Packing density (soil)
MD	Average potential maximum soil moisture deficit; disturbing moment of slope
pF	Soil suction expressed as common logarithm of suction or negative hydraulic head measured in centimetres of water
pH	A measure of soil reaction (acidity or alkalinity) on a logarithmic scale of 1–14
P	Rainfall interception factor
R	Radius of failure plane of segment of slope; annual rainfall
S	Soil shear strength
T	Total pore space; tensile root force acting at base of slice
T_R	Average tensile strength of root in fibre
t_R	Average tensile strength of root fibre per unit area of soil
u	Pore water pressure at slip surface
u_r	Decrease in pore water pressure due to evapotranspiration by vegetation at slip surface
ε	Porosity (soil)
γ	Unit weight of soil
γ_d	Dry unit weight of soil
γ_{sat}	Unit weight of saturated soil
γ_w	Unit weight of water
ρ	Density of soil
ρ_a	Density of air
ρ_b	Bulk density of soil

ρ_d	Dry bulk density of soil
ρ_s	Particle density
ρ_w	Density of water
ΔS	Increase in soil shear strength
$\Delta S'$	Increase in effective soil shear strength
ϕ	Angle of internal friction or shearing resistance
ϕ'	Effective angle of internal friction or shearing resistance
σ_n	Normal stress
σ'_n	Normal effective stress
τ_R	Maximum bond stress or pull-out resistance between root and soil

1 Introduction

1.1 BACKGROUND

Vegetation is widely used in civil engineering as a way of reducing the visual impact of civil engineering works and enhancing the quality of the landscape. It can also perform an important engineering function because of its direct influence on the soil, both at the surface, protecting and restraining the soil, and at depth, increasing the strength and competence of the soil mass. Vegetation can also very significantly affect soil moisture. All these effects may be adverse or beneficial, depending on the circumstances, and most have direct engineering relevance; *see* Figure 1.1.

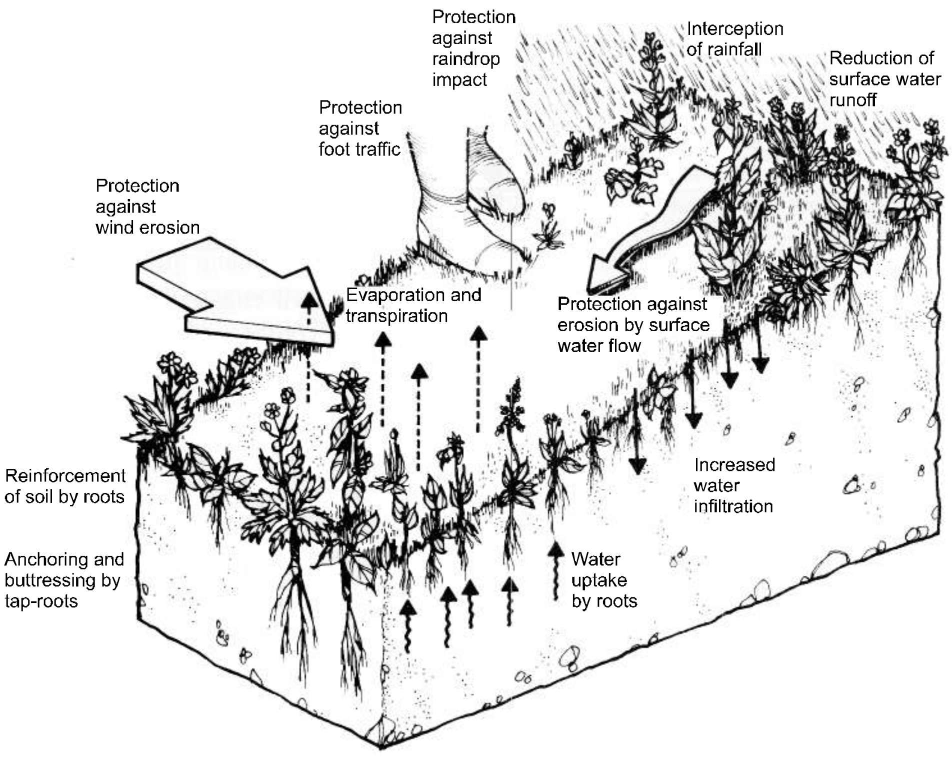


Figure 1.1 *Some influences of vegetation on the soil*

The engineering use of vegetation is termed "bioengineering" and this guide introduces a range of bioengineering applications relevant to the UK construction industry. The majority relate either to the restraint of surface soil particles or the stabilisation of a soil mass. These applications are summarised in Box 1.1.

Box 1.1 *The applications of vegetation to related engineering situations*

Applications	Engineering situations												
	Mining and reclamation	Highways and railways	Construction sites	Waste disposal and public health	Airfields and helipads	Waterways	Land drainage	Reservoirs and dams	Coastal and shoreline protection	Buildings	Recreation	Pipelines	Site appraisal
Slope stabilisation – embankments and cuttings	●	●	●					●	●				
– cliffs and rockfaces	●	●							●				
Water erosion control – rainfall and overland flow	●	●	●	●			●	●	●		●	●	
– gully erosion	●	●	●			●	●	●	●		●	●	
Watercourse and shoreline protection – continuous flow channels						●	●						
– discontinuous flow channels	●	●		●		●	●		●	●			
– large water bodies (shorelines)								●	●				
Wind erosion control	●		●	●	●				●		●	●	
Vegetation barriers – shelter	●	●		●		●			●	●	●		
– noise reduction		●		●						●			
Surface protection and trafficability			●		●	●		●	●	●	●	●	
Control of runoff in small catchments	●	●	●	●		●	●				●		
Plants as indicators	●			●		●		●				●	●

The guide is written primarily for the practising civil engineer and therefore assumes some familiarity with the engineering context of bioengineering applications. However, many engineers are unfamiliar with the use of vegetation as an engineering material. This is because bioengineering requires both an understanding of engineering principles and a knowledge of vegetation and the way it interacts with soil, water and climate. Such knowledge is not generally a part of civil engineering training and practice, which tends to emphasise the use of inert materials such as steel, concrete and timber, rather than live vegetation. The guide provides the reader with an understanding of the principles and procedures involved in bioengineering and how these can be employed. It also identifies areas where the engineer must seek specialist advice on the selection and establishment of vegetation. In this context, it is expected that the guide will also be helpful to the vegetation specialist in indicating the kinds of situations in which advice may be sought.

The principles and procedures brought out in the guide are applicable to a wide range of climates and soils, but the applications presented, together with specific information on climate, soils and plant species, have been selected to reflect UK conditions. In some cases, procedures are set out on a formal basis for the first time.

Some of the information contained in the guide comes from experience in central Europe and North America where physical and institutional conditions have led to the more widespread practice of bioengineering than in the UK. The book *Sicherungsarbeiten im Landschaftsbau* by Hugo Schiechtl (1973), quickly became a standard work on the European approach to bioengineering and was translated into English in 1980 at the University of Alberta Press. *Biotechnical slope protection and erosion control* by Donald H Gray and Andrew T Lieser (1982) is the standard work dealing with North American practice. In 1984 David Bache and Iain MacAskill produced their book on *Vegetation in civil and landscape engineering*, and this marked a departure for engineers in the UK. *Specification for highway works* (HMSO, 1986) deals in a more comprehensive way with the completion of earthworks than *Specification for road and bridgeworks* (HMSO, 1976), which it replaced. This progression points to a growing awareness of the importance of vegetation in construction.

Despite many years of experience in Europe and North America, however, the engineering role of vegetation is still imperfectly understood. There are many questions to be answered. For example, to what extent can this role be quantified? Is the level of quantification sufficient to enable design procedures using vegetation to be established? Can vegetation provide economic and environmental advantages over conventional engineering materials, and can it extend or enhance the performance of these materials? How much engineering experience is there on which to base designs using vegetation? This guide attempts to help the engineer answer these and other related questions.

Some uses of vegetation for engineering purposes have been well researched and documented, such as the design of grassed waterways. Other aspects are understood only qualitatively and the practice of bioengineering is very much an “art”, based on engineering experience and judgement, rather than an exact “science”. This guide provides an overview of present knowledge for a whole range of applications, from cases where the vegetative element can be “designed” on a rational scientific or empirical basis, to instances where the use of vegetation is largely based on an intuitive feel for what is right. The information and technical content of the report have been selected to demonstrate the present “state-of-the-art” and also to illustrate its limitations.

While bioengineering will necessarily continue to encompass both art and science, future research will undoubtedly develop further the scientific base and extend the frontiers of engineering knowledge and practice. Whatever the scientific basis of a bioengineering design, however, the engineer should recognise that its results will be judged by others as much on its environmental attractiveness as on its engineering suitability. In reality, it is often difficult to draw a clear distinction between the engineering and landscaping roles of vegetation. In all cases the engineer must seek to satisfy both engineering and environmental design criteria.

Three specific aspects related to the effects of vegetation in engineering are not covered.

1 Vegetation in relation to buildings: damage due to water removal on shrinkable clay soils; root penetration of foundations and drains; risk of toppling onto buildings.
2 Vegetation in relation to water quality: choking of waterways with plant growth as a result of eutrophication; the use of reed beds for land treatment of effluents and nutrient harvesting.
3 Vegetation growth on structures: adverse effects on weathering, corrosion or performance of concrete and steel.

It is not the intention of this guide to provide a design manual, or to convert the engineer into a vegetation specialist. Instead, the aim is to bridge the gap between the various disciplines that combine to make up bioengineering and to promote discussion between the engineer and the vegetation specialist. Thus this publication is an educational document as well as a practical guide.

1.2 Structure of the guide

Following this Introduction, the guide is divided into five sections. These are ordered so that readers approaching the subject for the first time are taken logically through the basic aspects of plants and their growth, the principles of the engineering effects of vegetation, methods of vegetation establishment and management, and applications of bioengineering. Readers with a specific application in mind, and using the guide as a source of reference, may prefer to use it in the reverse order, identifying the application and design guidelines, deciding on the method of approach and its implementation, and then referring to the techniques of vegetation establishment and management. Cross-referencing to the basic principles of the engineering effects of vegetation and the aspects of plant growth can be made as necessary, making particular use of the information presented in "boxes" rather than in the text.

The sections of the guide are summarised below:

1. *Introduction.* Background to the guide; its aims and objectives.
2. *Basic aspects of vegetation.* Theory and understanding of the structure and growth of vegetation and its interaction with the soil, water and climate.
3. *Physical effects of vegetation.* Theory and understanding of the properties and functions of vegetation in an engineering role; adverse and beneficial effects.
4. *Vegetation selection, establishment and management.* Techniques of site preparation, vegetation establishment and management; guidance on quality control.
5. *Method of approach and implementation.* Strategy, approach to planning, investigation, design, construction, establishment and maintenance; contractual implications; check list for comparing costs.
6. *Applications.* Practical applications of vegetation by the UK construction industry (*see* Box 1.1).

A full bibliography and list of references is included for those who require more detailed information on any subject covered in the guide. A list of plant species appropriate to the UK, with their bioengineering properties and the roles they can perform; relevant standards and sources of independent advice and information are given in the Appendices.

A glossary contains definitions of key technical terms, particularly those where conventional use differs between the engineer and the vegetation specialist.

A notation list is included to help the reader, particularly where conventions differ between different disciplines or where the same symbol is used to denote different terms, depending on the context. In general, technical terms and notation conform to civil engineering convention.

2 Basic aspects of vegetation

To appreciate how vegetation functions and should be managed, engineers need an understanding of the requirements of plants and plant communities, and of their behaviour under different conditions and circumstances. This section reviews those aspects which are relevant to the performance and use of plants in an engineering context.

2.1 Plant form and structure

Plants exhibit many different forms and structures, but in general those elements that an engineer is likely to work with can be considered to comprise:

- roots, to provide anchoring and absorb water and nutrients from the soil
- stems, to support the above-ground parts
- leaves, to trap energy in the form of sunlight for the manufacture of carbohydrate compounds
- flowers for reproduction.

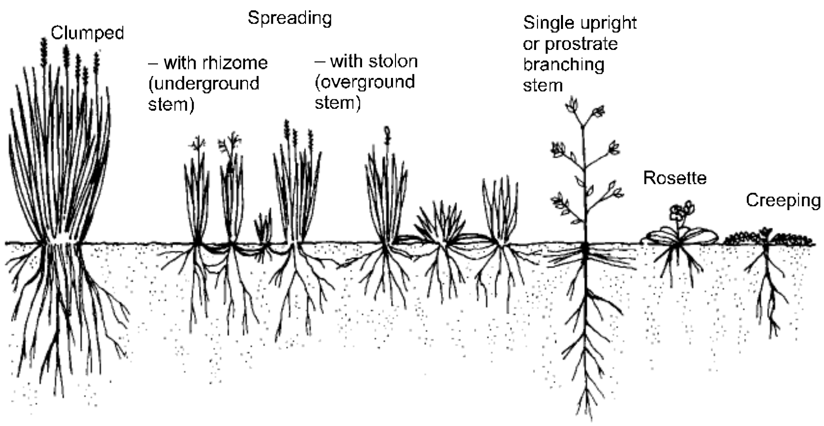
Some typical growth habits and structures are illustrated in Figure 2.1. Four plant groups will be considered here: trees, shrubs, grasses and herbs.

2.1.1 Trees

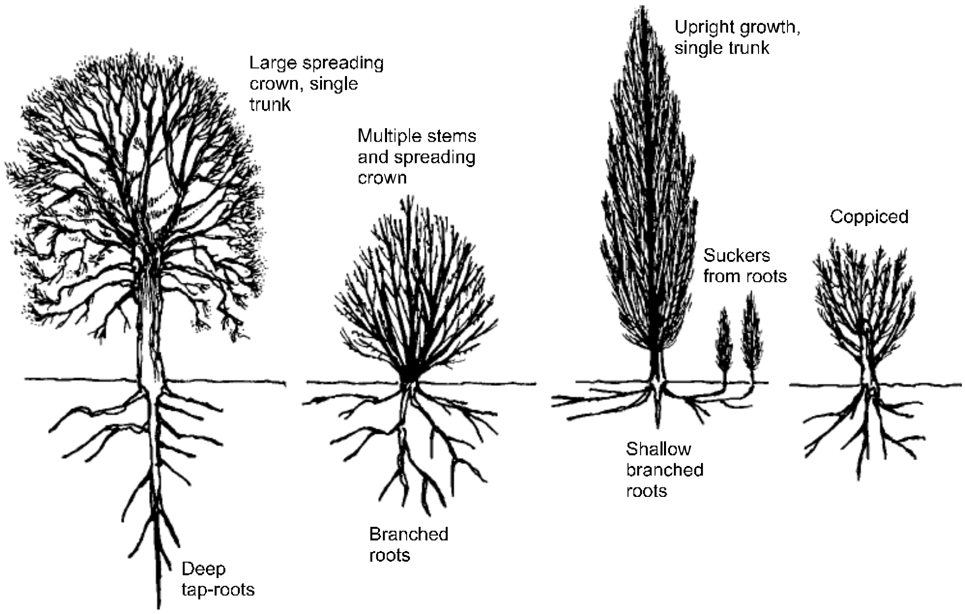
The growth habits of trees can vary considerably, even within one species growing in different environments. Most trees grow from a single upright main trunk which branches in the upper part to form a crown, the size of the crown determining the overall stem spacing. Densely-spaced plantations will tend to grow as a mass of tall thin stems with small crowns. Some species can spread by root suckers and form dense thickets. Coppicing and less severe forms of pruning are the usual ways of manipulating and perpetuating the above-ground growth of trees (Section 4.7).

2.1.2 Shrubs

Typically, shrubs have a fairly dense, woody, perennial growth, with many well-branched stems. Some shrub species are quite low-growing, for example cotoneaster grows to a height of about 300–400 mm, while others, such as gorse, broom and hawthorn, can grow to over 2 m.



(a) Grasses and herbs



(b) Trees and shrubs

Figure 2.1 *Some typical plant growth habits (not to scale)*

2.1.3 Grass

The grasses are a widespread and versatile family of plants, widely used by man for a variety of purposes. A grass sward is the commonest use of vegetation in an engineering context, and usually contains a variety of grasses together with herbs such as clover. Grasses give quick establishment and dense ground cover, respond well to many different management techniques and allow a range of land-uses.

Grasses spread vegetatively by tillering, that is by producing new stems from the bases of existing ones. The new tillers either cluster at the base of the existing plant, forming large clumps of densely packed plants, or they form on rhizomes or stolons to produce a spreading sward (*see* Figure 2.1). Rhizomes and stolons are stem structures, the former growing below-ground and the latter spreading across the surface. Rhizomes are particularly useful in bioengineering, as they can form a mass of tough underground stems with considerable structural strength, but in grasses they rarely grow very deeply.The single most important factor in the growth habit of grasses is that the main growing points are at ground level. This means that moderate mowing, grazing, burning or abrasion does not do any lasting damage to the plant.

2.1.4 Herbs

Herbs are broad-leaved plants of which the above-ground parts are generally non-woody. They include what are generally referred to as wild flowers and weeds, together with cultivated and forage plants such as legumes (eg pea, clover, vetch and lupin). Growth habits vary from upright single-stemmed or multi-stemmed individuals to spreading, creeping individuals.

2.1.5 Root systems

Root systems are of particular interest to engineers because of their fundamental importance to most of the functions that vegetation can perform. They vary from very fine fibrous systems through branched systems to a vertical taproot. All plants have a mat of surface roots, the main function of which is to collect nutrients, and which grow in and around the surface soil layers because this is where mineral nutrients are generally available. Deeper roots are used for anchorage and for absorbing water. Large taproots are often associated with the storage of food for over-wintering plants, especially where the above-ground parts die back substantially. The taproots are thus perennial structures whereas fine fibrous roots are subject to annual cycles of decay and renewal.

The greater part of the root system has one purpose: to extract water. A range of common forms is illustrated in Figure 2.2. Individual species vary in their rooting behaviour but soil type and the groundwater regime strongly influence root development. Roots in well-drained soils therefore have to go deeper and exploit a much larger volume of soil than those in moister soils, while a high groundwater level or a layer of densely-compacted soil will force roots to spread laterally; *see* Figure 2.3. The majority of roots are usually found within 300–400 mm depth in herbaceous vegetation, and up to 3 m deep in vegetation dominated by trees and shrubs. Although much greater rooting depths are often quoted, the proportion of roots at lower depths is usually very small.

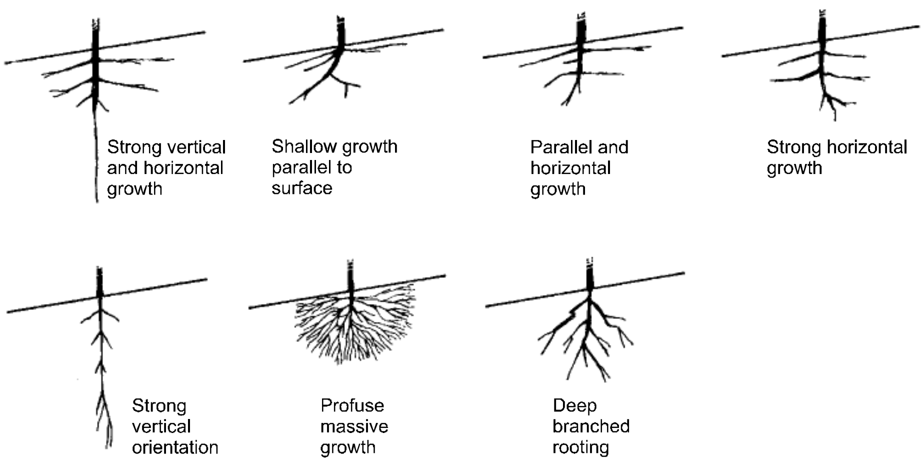


Figure 2.2 *Different patterns of root growth (after Yen, 1972)*

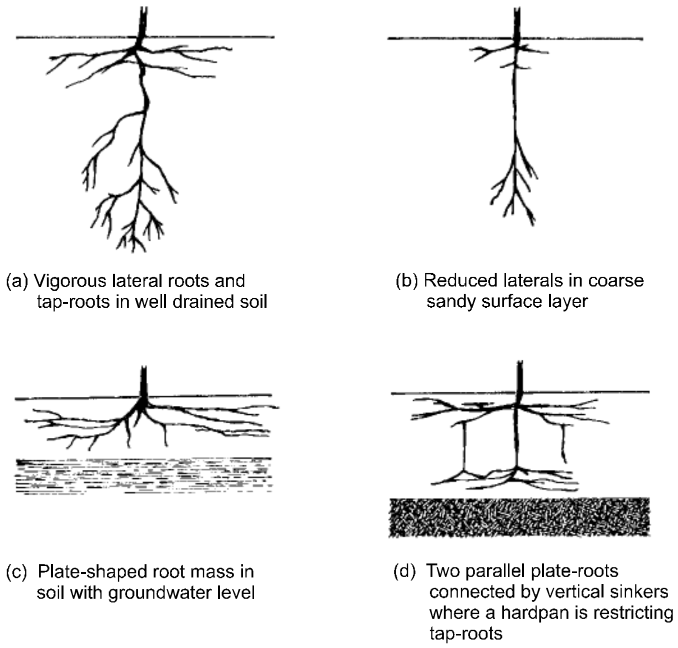


Figure 2.3 *Modification of root distribution by site conditions*

As grasses are widely used as ground cover, it is worth considering the characteristics of their root systems in more detail. Some 60–80 per cent of the grass root mass is found in the top 50 mm of soil, and requires three to four years to become fully developed. The root systems, as shown in Plate 2A, are highly branched and fibrous, forming a mass of fine roots most of which are short-lived, lasting only a year or so. There is a constant cycle of renewal, but the part of the root system which is active is greatly reduced during the winter period (*see* Section 2.1.6).

Plate 2A *Soil permeated with fibrous roots of grass and clover. Note that the densest root growth is in the top 50 mm or so*

The extent of root systems, especially of trees, can be considerable. Helliwell (1986) proposes a method of estimating the extent of tree roots, summarised in Box 2.1. The "zone of influence" of trees on shrinkable clay soils is considered to be about 1.5 times their height for high water demand species, 0.75 times for medium water demand species and 0.5 times for low water demanders (NHBC, 1985). These estimates give some indication of the potential extent of tree root systems but they need to be modified to take account of different soil types and groundwater conditions (*see* Figure 2.3).

The application of tensile or compressive forces to roots stimulates them to thicken. For example, it has been observed that on slopes the thickest roots run obliquely up-hill, functioning as anchors. Root tensile strengths have been measured, and typical ranges of values are given in Table 2.1, but there is great variation according to size and age, plant species and site conditions.

Box 2.1 *A method for estimating the extent of tree root systems (After Helliwell, 1986)*

This is based on the rule of thumb that a tree requires a root system occupying a volume of soil equal to one-tenth of the volume occupied by the crown (branches and foliage). This estimate is then modified by multiplying it by:

1) (average maximum potential *SMD/200*) + 0.2
   where *SMD* is the soil moisture deficit,
   to allow for the effect of likely drought.
2) 15% of the available water capacity
   to allow for the soil droughtiness.
3) a figure related to the soil fertility:

– very fertile soil	0
– moderately fertile soil	0.8
– low fertility	1.0

4) a figure related to the degree of wind exposure:

– sheltered climate	1.0
– windy climate but tree in a large group	1.5
– single isolated tree in moderately windy area	1.5
– isolated tree in a windy area	2.0

The actual depth and spread of rooting will depend on soil and groundwater conditions as well as species.

This method is very approximate, and does not allow for the difference between species in density of foliage, rate of moisture loss and nature of the root system.

The density of roots in a volume of soil is a significant parameter and can be assessed by a number of methods:

- measuring Root-Area-Ratio (RAR), the proportion of the cross-sectional area of a sample section of soil that is occupied by roots
- weighing the mass of root separated (by washing and sieving) from the soil volume. This will tend to underestimate the quantity of finer roots
- estimating the length of root in a sample using the line intersection method of Newman (1966).

Methods of investigating root systems are reviewed by Bohm (1979).

2.1.6 Seasonal growth pattern

Seasonal patterns in plant growth and distribution are very significant in relation to engineering function. All vegetation follows an annual cycle of growth, reproduction, die-back and dormancy. Plants are generally dormant over the winter period, and the way in which they cope with this period is important in considering their engineering behaviour. A typical annual cycle of active plant growth is illustrated in Figure 2.4.

In annual species, the cycle of germination, growth, flowering, seeding and senescence is completed in one growing season. Perennials persist from year to year by a variety of strategies, illustrated in Figure 2.5. Evergreen plants such as pines do not shed their leaves for the winter but have other mechanisms to reduce activity during dormancy. Their leaves are usually stiff and waxy in order to survive the cold and reduce transpiration. Deciduous species shed leaves and may die partially or completely back to ground level during the winter.

Table 2.1 *Tensile strengths of roots of selected plant species (after Schiechtl, 1980; O'Loughlin and Watson, 1979)*

Grasses and herbs	***Tensile strength (MN/m²)***
Elymus (Agropyron) *repens* (Couch grass)	7.2–25.3
Campanula trachelium (Bellflower)	0.0–3.7
Convolvulus arvensis (Bindweed)	4.8–21
Plantago lanceolata (Plantain)	4.0–7.8
Taraxacum officinale (Dandelion)	0.0–4.4
Trifolium pratense (Red Clover)	10.9–18.5
Medicago sativa (Alfalfa)	25.4–86.5
Trees and shrubs	
Alnus incana (Alder)	32
Betula pendula (Birch)	37
Cytisus scoparius (Broom)	32
Picea sitchensis (Sitka Spruce)	23
Pinus radiata (Radiata Pine)	18
Populus nigra (Black Poplar)	5–12
Populus euramericana (Hybrid Poplar)	32–46
Pseudotsuga menziesii (Douglas Fir)	19–61
Quercus robur (Oak)	32
Robinia pseudoacacia (Black Locust)	68
Salix purpurea (Willow)	36
Salix cinerea (Sallow)	11

The figures given above for live roots are the ranges measured by various workers. When roots die there is some residual strength which will persist. Figures given by O'Loughlin and Watson (1979) indicate this for one species (*Pinus radiata*) as follows:

	Minimum		Maximum	
	Tensile strength (MN/m²)	Diameter (mm)	Tensile strength (MN/m²)	Diameter (mm)
Living trees	7.6	0.13	37.5	1.4
3 months since felling	2.9	0.2	33.3	1.1
9 months since felling	2.9	0.2	43.3	1.5
14 months since felling	2.7	0.2	30.9	1.5
29 months since felling	0.3	0.3	14.3	1.8

Tensile strengths of roots will vary considerably with age, size and season. The overall strength of roots penetrating soil will depend on the density and orientation of the roots as well as their individual strengths. For these reasons the figures given should be interpreted with caution. There is no comprehensive list of species which gives root strengths. Further data are quoted by Stiny (1947), Turmanina (1965), Hiller (1966), Kassif and Kopeloritz (19681, Chang (1972), Hathaway and Penny (1975), and Waldron and Dakessian (1981).

The ability of a plant to function satisfactorily as an engineering component during the dormant period is most important. It is then that the above- and below-ground plant biomass is at a minimum, reducing the shielding and root reinforcement effects. As an example, the seasonal root growth and distribution below a grass sward are illustrated in Figure 2.6. Metabolic activity and transpiration are also lower during winter, reducing the effects of the plant on soil/water relationships. As growth is reduced, so is the ability to self-repair in the event of damage. It may be necessary to maximise the growth of a certain part of a plant, such as the roots, during the active growing season, so that the carry-over effect into the dormant season is sufficient to fulfil the functional requirement, which may be more pressing in the winter.

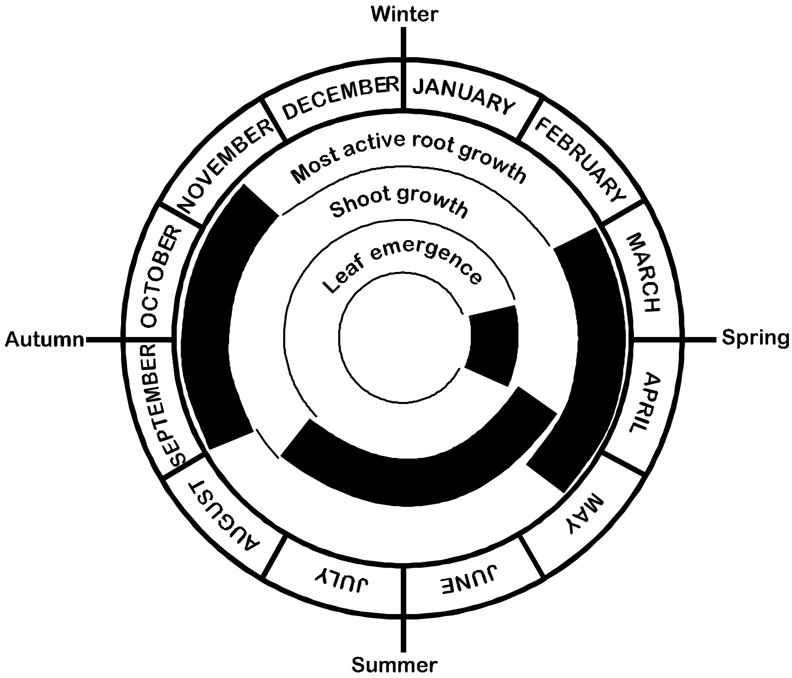
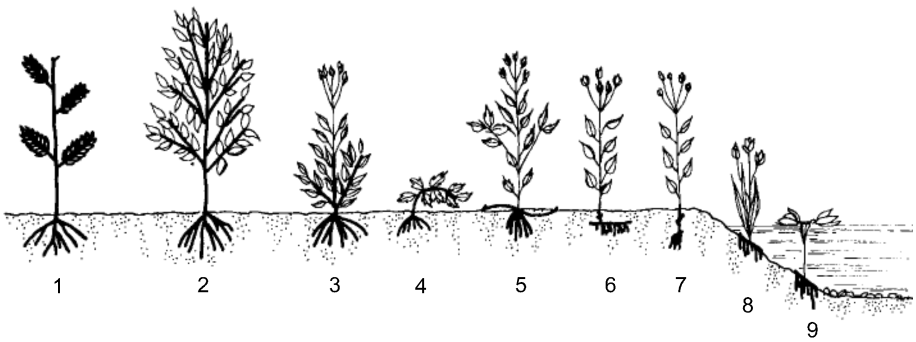


Figure 2.4 *A typical annual cycle of active plant growth (shaded) for southern UK*



1	Evergreen plants that reduce activity (eg conifers).
2	Deciduous plants that shed leaves.
3, 4	Perennating parts, borne very close to the ground, the remainder dying.
5	Perennating parts at ground level, all above ground herbage dies back.
6–9	Perennating parts below ground or submerged in water.

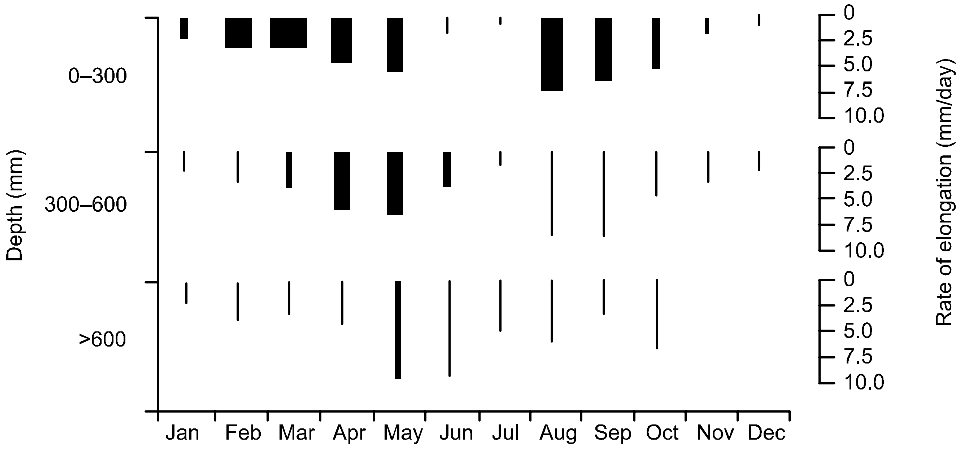
Figure 2.5 *Various strategies for overwintering of perennial plants (after Raunkiaer, 1934)*

2.2 Vegetation and plant communities

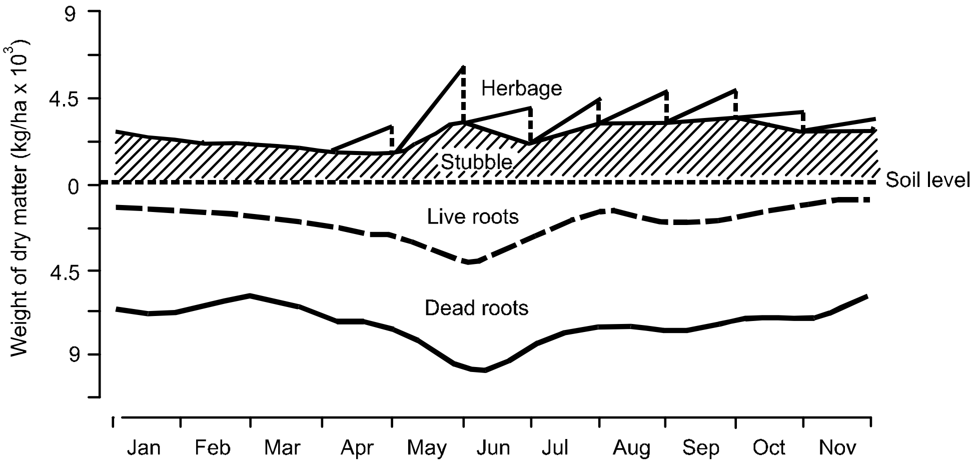
Plants not only exist as individuals but interact with each other to form dynamic communities. It is therefore important to consider the structure and function of plant communities.

2.2.1 Community structure

Natural assemblages of plants which are recognisable as a unit are termed "communities". These are defined by their species composition and are associated with specific characteristics of climate, soil and management. Although apparently stable, communities are dynamic with a continual turnover of individuals. When some factor changes, such as climate, ground conditions or grazing, the community will adapt accordingly.



a) Mean daily rate of elongation of ryegrass roots (width of symbol is proportionate to the number of roots)



b) Distribution of dry matter throughout a ryegrass sward, cut to 50 mm once a month

Figure 2.6 *Root growth and distribution with season for a ryegrass sward (from Garwood, 1967a)*

A recently-established plant community, such as a sown grass sward or a tree plantation, may consist of a small number of species and bear little relation to a natural or semi-natural community. The extent to which a community will change depends largely on management. For example the species composition of a football pitch is maintained by a high level of management. If that management should cease, then species composition will change, quite rapidly at first but more slowly as it approaches a more natural composition.

2.2.2 Vegetation structure

Vegetation has a three-dimensional structure. In plan there is a spatial distribution of individual plants of different shapes and sizes, with some degree of overlap in both above- and below-ground parts. In vertical section there are usually distinct layers which are characteristic of the type, age, status and management of the community.

Swards of grass and herbaceous vegetation have a fairly simple structure, as shown in Figure 2.7 and Plate 2B. When they are not grazed or cut very frequently they become a tall-grass community with a fairly dense growth; a litter layer usually accumulates and a dense root mat develops. Grazed or frequently cut swards have a much shorter, more compact growth, with a higher shoot density but less root mass. The litter layer is less well developed, as defoliation removes much of the above-ground biomass.

Woody vegetation with trees and shrubs can have a well-developed stratification, with a dense canopy, an open shrub layer and a generally sparse ground cover. Structure in a tree plantation depends on the age and maturity of the plantation, as illustrated in Figure 2.8. The dense shade beneath some tree species, such as beech, limits the development of the shrub and ground flora. The structure of very young plantations resembles that of swards, until the canopy closes over. Shade then becomes a dominant factor in controlling the stratification beneath it.

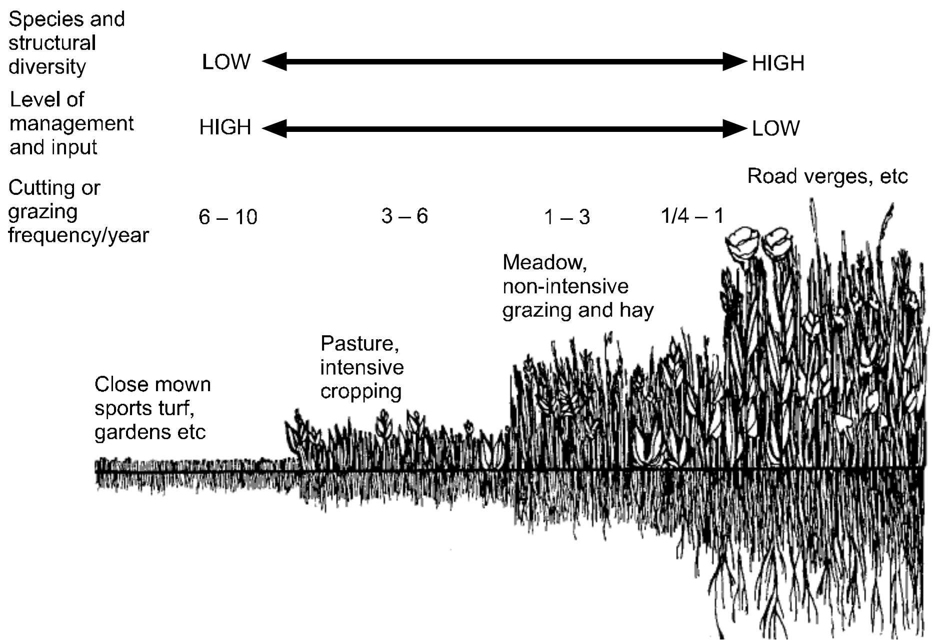


Figure 2.7 *Grass sward structure as influenced by levels of management*

The litter layer is an important component of the vegetation structure, forming a continuous protective layer over the soil surface. The system of roots, rhizomes and suckers is stratified in a way similar to the above-ground parts as shown in Figure 2.9.

Plate 2B *Typical short grass and herb community*

2.2.3 Succession

The concept of vegetation as being dynamic has already been introduced. Change can occur in response to a changing climate, soil environment, or management regime. A more important type of change is a natural succession towards a climax community, through a number of progressive (seral) stages.

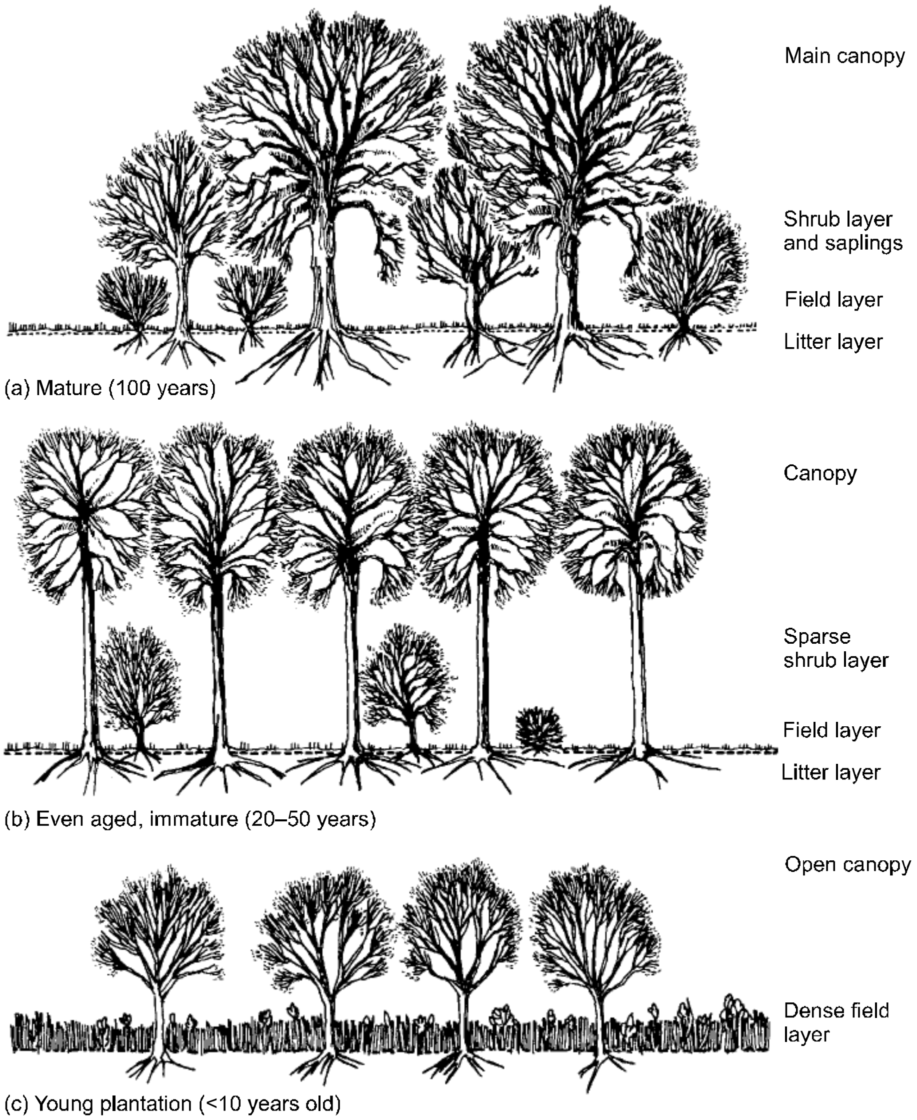


Figure 2.8 *Tree plantation structure at various stages of development*

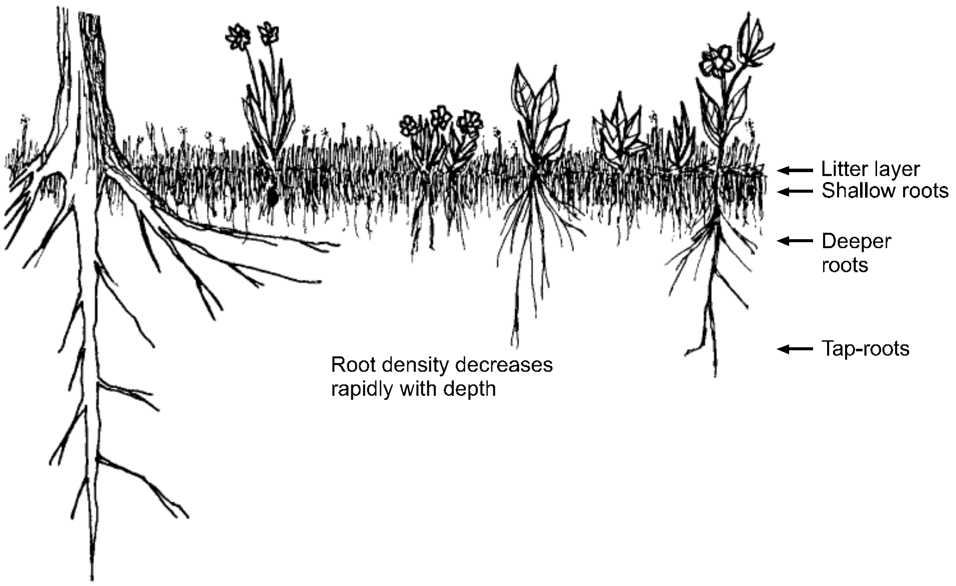


Figure 2.9 *Below ground vegetation structure: stratification of root systems*

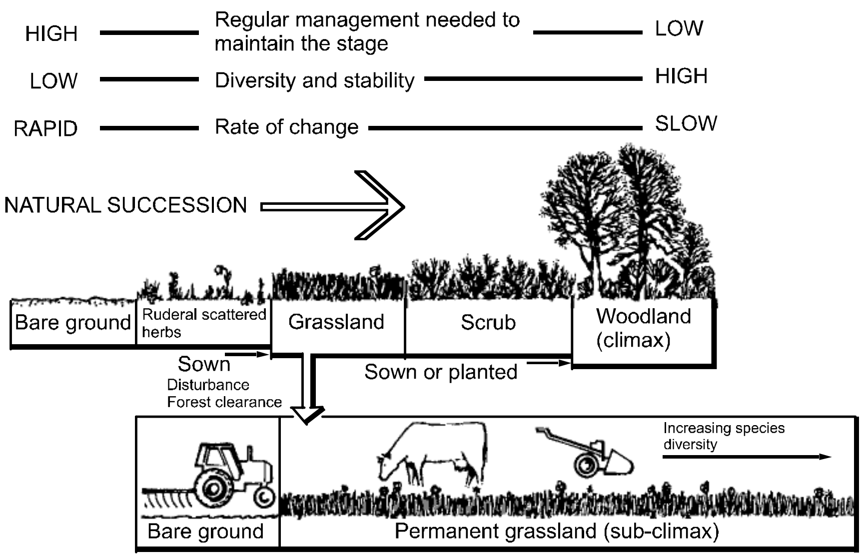


Figure 2.10 *Natural succession in plant communities of temperate European climates*

The theoretical climax or *potential natural vegetation* is that which would develop under the prevailing climatic, soil and historical conditions, including any previous man-made changes, if all current human influences were removed (Tuxen, 1956). From this notional climax, it is possible to make deductions about the associated pioneer and successional plant communities and the individual species which they comprise.

For most of the UK the theoretical climax or potential natural vegetation is woodland, mainly oak but also beech, ash and, in the north, pine and birch. Given sufficient time, and the absence of any interference by man, the progress of succession, starting from bare ground, is one of herb and grass, scrub and then tree cover, as shown in Figure 2.10 and Plate 2C. In very exposed locations, close to coasts and in very mountainous or cold regions, the tree cover stage may not be reached.

(a) Young mixed plantation on a road cutting railway

(b) Mature tree growth (Sycamore) on a cutting

Plate 2C *Succession to tree cover*

Interference can deflect the natural succession from its usual path to produce a sub-climax. The most significant form of interference is due to man, who manages and manipulates the vegetation to maximise the benefits which can be gained from it. Examples of these sub-climaxes are grassed areas, maintained by grazing or cutting, and heather moorland maintained by burning. Herbaceous communities comprised mainly of grasses have been widely manipulated by man, and their character varies considerably with the management they receive (*see* Figure 2.7).

Succession implies a change in soil characteristics as well as species composition. Beginning with a subsoil or mineral spoil the following changes will occur progressively:

1 Organic matter content will increase.
2 Plant roots and soil animals will open up the soil, increasing water infiltration.
3 Weathering of large particles will reduce coarse particle sizes.
4 Soil structure will develop and clay flocculation will increase effective particle size in the finer fraction.

These changes generally result in a reduction in soil density and an increase in permeability.

This brief discussion of succession has been included to underline the extent to which management of vegetation is important. Rarely will an engineer embark on an engineering design relying totally on a climax vegetation because of the time needed to reach that stage. He might, however, anticipate a progression to this state, making use of earlier intermediate stages, or alternatively a management strategy (eg grass cutting) might be adopted which seeks to ensure that natural succession does not take place. In either case the engineer must be aware of what changes can take place, and the natural forces on which they depend.

2.2.4 Plant strategies and competition

Plants have a number of strategies for exploiting their particular environment. A plant community is made up of species which compete with each other in various ways for sources of light, water and nutrients. The external factors which species have to deal with can be summarised in two categories:

1 Stress, brought about by restrictions in light, water, mineral nutrients, temperature.
2 Disturbance, arising from the activities of man, herbivores, pathogens, damage, erosion and fire.

It has been suggested (Grime 1979) that plants have adopted three strategies for dealing with various intensities of environmental stress, such as infertile or drought-prone soil, and disturbance. *Competitors* exploit conditions of low stress and low disturbance; *stress-tolerators* exploit high stress and low disturbance; and *ruderals* (eg weeds) exploit low stress and high disturbance. In reality many different plant species exhibit various degrees of each strategy, being intermediate between the three extremes. A review of plant strategies for a wide range of UK species is given in Grime *et al* (1988).

The practical implications of the concepts of plant strategies and niches within a community are that mixtures of species have to be designed to take account of plant community dynamics and the characteristics of a site. In general, the first colonisers of bare ground will be ruderal plants, and the direction in which vegetation will develop subsequently depends on the relative stress due to climate or soil. Where stress is not very great, such as where good topsoil is used, progression will be from ruderal to competitive communities. Where stress is greater, due to the soil or climate, the plant community will progress towards stress-tolerant species.

2.3 Basic requirements of plants

Plants need light, air, water and nutrients, as shown in Figure 2.11. Since even healthy vegetation growing in topsoil may not be performing ideally in an engineering sense, all aspects of the soil/plant system and the various interactions involved need to be considered. For a detailed consideration of plants and soil, refer to Wild (1988). Deficiencies in plant requirements are most apparent in hostile environments. Most construction sites can be considered hostile to plants in some way. Box 2.2 summarises the main problems which occur and these are described in detail in Bradshaw and Chadwick (1980) and Coppin and Bradshaw (1982). The environmental requirements relevant to plant growth are considered under two headings:

1 Plants and soil: the capacity of the soil to support vegetation.
2 Plants and climate: the bioclimate affecting the choice and performance of plants.

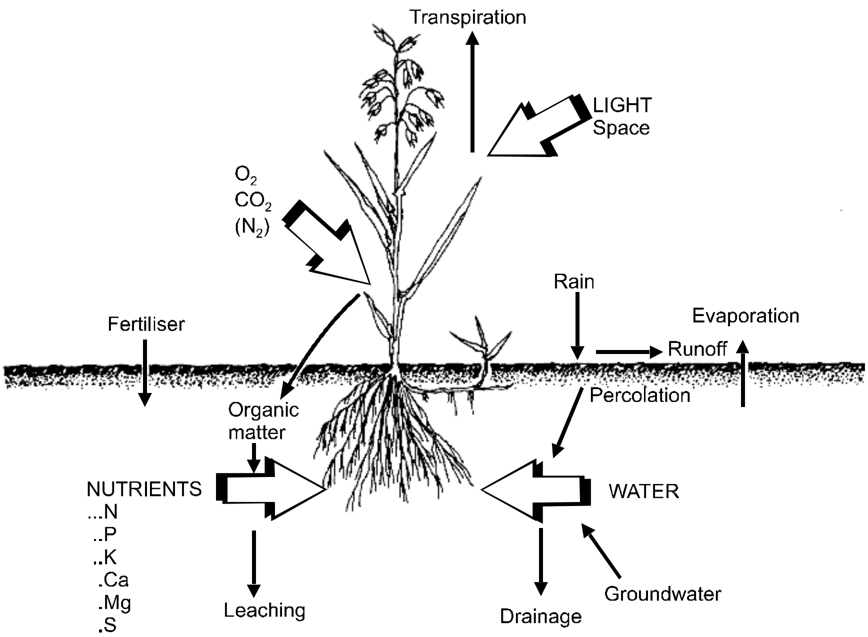


Figure 2.11 *Basic needs of plants*

Box 2.2 *Plant growth problems on hostile sites*

Problem	*Consequence*
Physical	
Shallow rooting depth	Drought effects, poor root development
Coarse soil texture	Poor water holding capacity
High soil density, compaction fine soil texture	Low water infiltration, high runoff, poor root penetration
Steep slope	Surface instability, high water runoff
Chemical	
Low nutrients	Infertility, especially nitrogen
Low exchange capacity	High leaching of nutrients (c.f. coarse soil texture)
Low pH	Acidity, nutrients unavailable
Toxicities	Salt, heavy metals
Climatic	
Low rainfall	Drought
High rainfall	Erosion, soil loss, leaching of minerals
Cold	Slow plant growth, short growing season
Aspect	Other effects modified, eg drought and cold
Exposure	Erosion, physical damage to vegetation, growing season reduced

Box 2.3 *Soil physical parameters (definitions relating to plant growth*

Parameter	*Definition*	*Assessment*
Soil texture	Description based on proportions by weight of sand, silt and clay as percentages of fine earth fraction <2 mm in size	Field estimations or laboratory measurement
Stoniness, % vol	Proportion of large particles, >2 mm	Direct measurement, or field estimation
Dry bulk density* (ρ_d) Mg/m^3	Apparent density of soil *in situ* (on a dry basis)	Field measurement, either removal of undisturbed core or replacement method (sand or water)
Particle density* (ρ_s) Mg/m^3	Density of the soil particles	Laboratory measurement by displacement. Most soils are consistent with a value about 2.65 Mg/m^3
Void ratio (e)	Ratio: volume of soil voids to volume of solids	$e = \rho_s/(\rho_b — \rho_s)$
Porosity (ε) %* (total pore space, T)	Volume of soil voids expressed as a percentage of total in situ soil volume note – voids occupied by air and water.	$\varepsilon = (1 — \rho_b/\rho_s) \times 100$
Soil erodibility factor	The risk of erosion by air or water due to the nature of the soil itself	Direct measurement or estimation based on soil texture, *see* Sections 6.3.2 and 6.5.2
Packing density (L_d)* (rooting potential)	A more reliable indicator of the effects of compaction than bulk density alone: allows for clay content	$L_d = \rho_b + (0.009 \times \%\ \text{clay})$

* See Hall *et al,* (1977), Jarvis and Mackney (1979).

2.4 Plants and soil

The terms “topsoil”, “subsoil” and “soil” are used throughout this guide in their accepted engineering sense (such as ICE 1976), except that the definition of soil is extended to include unnatural loose materials such as mine spoil and quarry waste, materials which figure frequently in earthworks. Soil scientists and vegetation specialists sub-divide the engineer’s simple topsoil and subsoil description into soil horizons, features which have developed from the parent material or rock (*see* Section 2.4.4).

Many of the physical properties of soil which are of interest to the engineer are equally important to the soil specialist, for example bulk density, moisture content, particle size and organic content. The latter’s traditional interest in these properties generally extends to the topsoil and subsoil only, and these are materials which the engineer has tended not to examine in such detail.

2.4.1 Physical properties of soil

Box 2.3 summarises the important physical parameters of the soil. The soil characteristics which affect vegetation establishment and growth, their principal determinants and the ways in which they can be modified are given in Box 2.4. Soil contains water, air, fine earth, stones and organic matter. The proportions of these components are illustrated in Figure 2.12.

Box 2.4 *Soil physical characteristics*

Important soil characteristics	Principal determinants				Modifiers					
	Particle size	Packing density	Porosity	Organic matter	Vegetation cover	Top-ography	Cultiv-ation	Compact-ion	Additions	Time
Texture	●									
Soil structure	●		●	●			○	○		○
Rooting potential	●	●	●	●			○	○		
Soil water capacity	●		●	●				○	○	
Permeability and water acceptance			●		○	○	○	○		○
Ion exchange capacity	●			●	○				○	
Erodibility	●		●	●	○	○	○	○		
Ease of cultivation	●	●	●			○		○	○	

Soil texture describes the particle size distribution and gives an indication of the likely behaviour of a soil in respect of handling, root growth or drainage. Descriptions such as sandy loam or clay are based on measured proportions and mixtures of clay, silt and sand in the fine earth (<2 mm) fraction, as shown in Box 2.5.

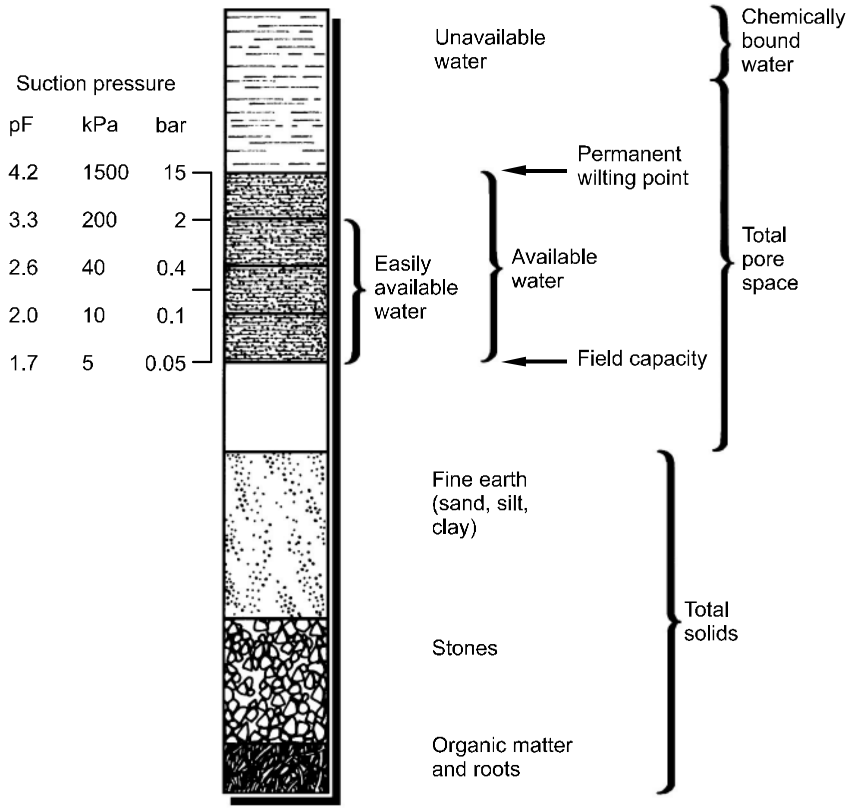


Figure 2.12 *Representation of the relative proportions (by volume) of various fractions soil*

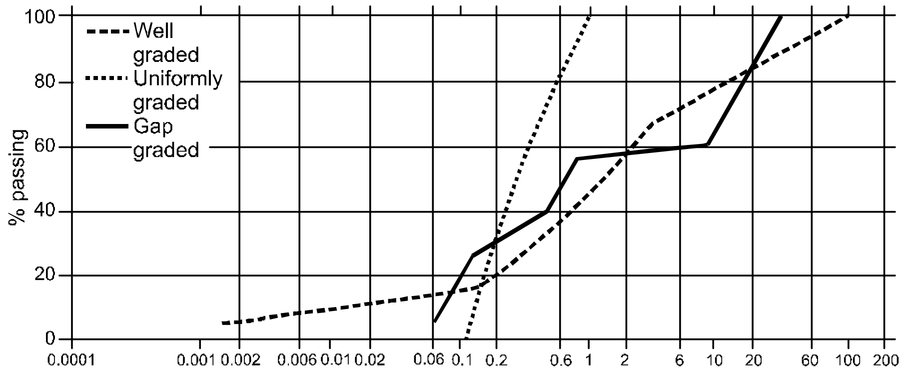
Rooting potential indicates the resistance of the soil to root penetration, which depends mainly on the soil's bulk density and on mechanical strength. Roots have great difficulty penetrating soil with strengths greater than 2.0 to 2.5 MN/m^2, though higher limiting values have been suggested for coarse-textured soils. Generally, root growth is enhanced by greater moisture content and voids, and is retarded by higher bulk density and clay content.

Critical dry bulk densities for soils, above which root growth is severely restricted, are about 1.4 Mg/m^3 for clay soils and 1.7 Mg/m^3 for sandy soils. As clay content is so important in determining the rooting potential, a term packing density (L_d) is often used to determine the maximum density to which a soil can be compacted and still permit root growth (*see* Box 2.3).

Soil structure is a characteristic which describes the arrangement and size of particle aggregates or "peds". Structure develops over time, as fine soil particles aggregate into crumbs and blocks. This increases the number of large pore spaces and thus the permeability and rooting potential of the soil. The presence of organic matter and plant roots plays a major role in developing and maintaining soil structure. Structure is easily damaged by handling or cultivation during wet conditions, when the soil is weaker.

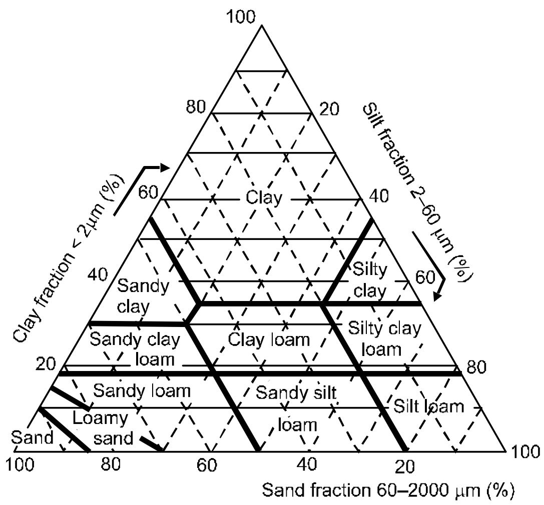
Box 2.5 *Soil texture*

The usual particle grading curves prepared to BS 5930: 1981 are familiar to most engineers. Soils are described according to the British Soil Classification System for Engineering Purposes.



Clay fraction	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	Cobbles
	Silt fraction			Sand fraction			Gravel fraction			
Fine earth							Stones			

For soil survey work, texture descriptions are based on the fine earth fractions, that is <2 mm size. The overall proportion of gravel and cobbles defines the *stoniness*. The proportions of sand, silt and clay in the fine earth soil matrix define the texture classes as given in the triangular diagram.



The proportions of sand, silt and clay can be obtained from the particle grading curve, calculating the quantity of each size fraction as a percentage of the <2 mm fraction.

Box 2.6 *Soil water parameters*

Parameter	*Definition*	*Assessment*
Soil water potential, N/m^2 or pF (soil suction and pore water pressure)	A measure of the suction power needed by roots, to extract water at a given soil moisture content. Defined as a function of the difference between the potential of water in the soil to that of pure free water at the same temperature, elevation and atmospheric pressure. The same measure as soil suction or pore water pressure	Direct measurement in soil using tensiometer
Field capacity (*FC*), % vol	The maximum equilibrium moisture content under free drainage, ie after excess water has drained away under gravity. Corresponds to a suction pressure of 0.05 bar	Measured using suction apparatus (sand bath) at 0.05 bar ($5kN/m^2$). Estimated from regression equation, topsoil $FC = 47 + 0.25(C) + 0.1(Z) + 1.12(X) — 16.52\ \rho_b$ subsoil $FC = 37.2 + 0.35(C) + 0.12(Z) — 11.73\ \rho_b$
Permanent wilting point (*PWP*), % vol (Retained water capacity)	The minimum moisture content which will sustain plant growth. Corresponds to a suction pressure of 15 bar	Measured using suction apparatus (pressure membrane) at 1.5 MN/m^2. Estimated by regression equations: topsoil $PWP = 2.94 + 0.83(C) — 0.0054(C)^2$ subsoil $PWP = 1.48 + 0.84(C) — 0.0054(C)^2$
Available water capacity (*AWC*), % vol	The difference between *FC* and *PWP*, theoretically the water available for plant growth under ideal conditions	Subtract measured/estimated values of *FC* and *PWP*. Estimate directly from equations: topsoil $AWC = 46.4 – 21.42(\rho_b)$ subsoil $PWP = 36.94 + 0.11\ (Z') – 18.45(\rho_b)$ or: $AWC = 1.25 – 0.01(CS + FS) + 0.25(X)$ mm/cm depth or from tables of typical values.
Air capacity (*AC*), % vol	The volume of air in a soil at *FC* (ie. at 0.05 bar suction)	Subtract *FC* from total pore space. Or, from sum of typical values
Profile available water (*PAW*), mm	Integration of the available water values for several horizons in a soil profile	*PAW,* mm = $(A_1H_1 + A_2H_2 + A_3H_3$ etc)/10 (where *A* is the *AWC* and *H* is the thickness of the horizon in mm). Integrate to 1 m depth or to impermeable horizon, whichever is shallower
Potential evapotranspiration (E_t), mm	Calculated water loss from a soil vegetated with a grass sward, assuming no limitations as a soil dries out	Penman equation, results published by Meteorological Office (*see* also Section 3.4.1)
Actual evapotranspiration (E_a), mm	Corrected E_t to allow for reduced water loss as a soil progressively dries out	
Soil moisture deficit (*SMD*), mm	Extent to which a soil dries out as E_a exceeds rainfall during the summer. Equivalent to the amount of rainfall needed to bring the soil back to *FC*	*See* Section 3.4.2 on estimating a soil moisture deficit. Data available from the Meteorological Office
Average potential soil moisture deficit (*MD*), mm	Measured/estimated value of *SMD* from long-term meteorological data	Published tables and plans (eg Bendelow and Hartnup, 1980)
Droughtiness	The likely intensity of moisture stress in a soil, based on *PAW* and *MD*	*PAW – MD*

C = Clay %, *Z* = silt %, *Z′* = (2–100 μm grade).
CS = coarse sand % (0.2–2mm grade).
FS = fine sand % (0.02–0.2 mm grade).
X = organic carbon %.
ρ_b = bulk density, Mg/m^3.
All % expressed as fine earth fraction <2mm.

2.4.2 Soils and water

Only the soil/water relations that affect plant growth are discussed here. The effects of vegetation on the overall soil moisture balance are discussed in Section 3.4.2. The implications of these effects on pore-water pressure and soil suction, and thus on soil strength, are considered in Section 3.6.

Soil water is usually defined in terms of water potential, being the difference between the chemical potential of water in the soil and that of pure free water at the same temperature, elevation and atmospheric pressure (Etherington 1982). Soil water potential is made up of two components:

1 The solute potential, ie the osmotic effect of dissolved salts; this is usually very small.
2 The matric potential, a function of the porous soil matrix in which water is held by capillary effects.

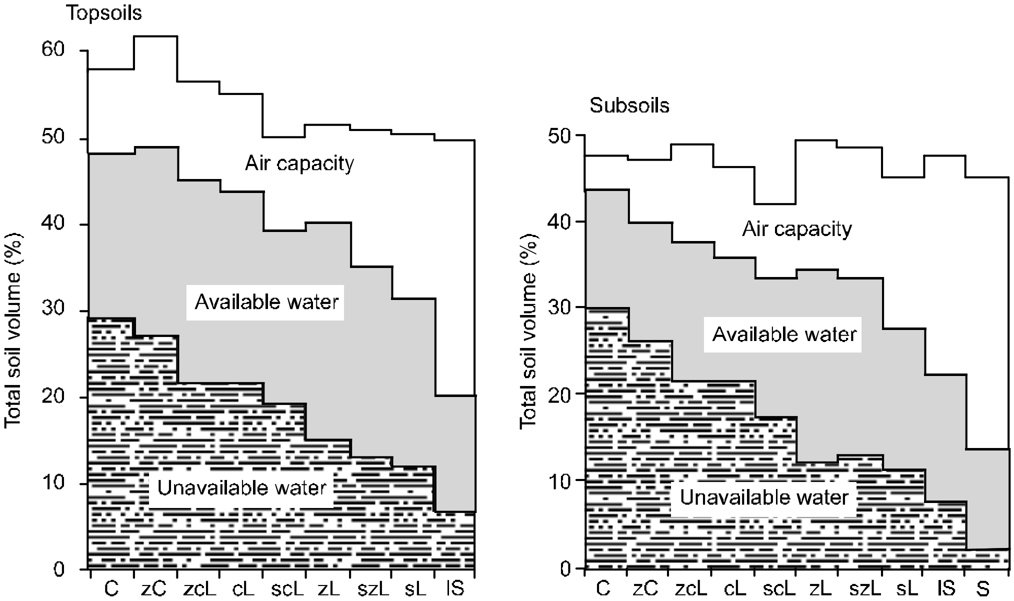
The soil water potential is therefore determined mainly by the physical properties of a soil, as shown in Box 2.6. Roots will only take up water when their water potential is less than that of the soil. Different plant species vary considerably in their "water potential". Water potential is usually measured in terms of pressure/suction: bars, kN/m^2 (kPa) or head of water. This is sometimes given in units of pF, defined as pF = $\log_{10}$ (negative hydraulic head of water in centimetres). However pF is no longer widely used.

The implications of soil water content as soil suction, or pore-water pressure, on the strength of a soil mass is discussed in Section 3.6. The influence of vegetation on the soil moisture balance, through rainfall interception, evapotranspiration and effects on soil permeability, is discussed in Section 3.4.

The *Available Water Capacity* (AWC) of a soil is the proportion of soil water normally available to plants (*see* Figure 2.12). It is the difference in water content between field capacity, the moisture content remaining when a soil has drained under gravity, and the permanent wilting point, the moisture content at which plants will not normally recover if soil moisture is further reduced. Even in freely draining soils, not all the AWC is readily available to plants and "easily available water" is considered to be about two thirds of the AWC of a profile. The relationships with soil texture are shown in Figure 2.13, and further data can be obtained from Jarvis and Mackney (1979).

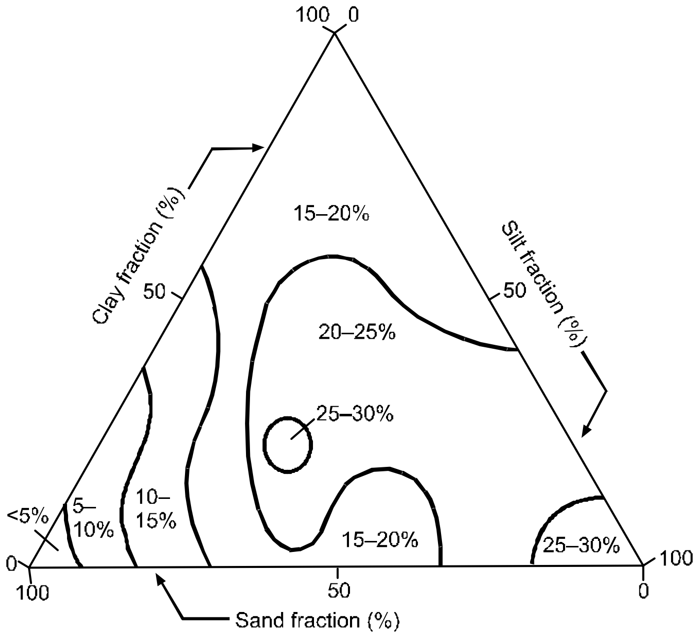
The *Profile Available Water* (PAW) is the total water over the whole soil profile, and represents the quantity of water available for plant growth. The limiting depth for the soil profile in calculating the PAW is frequently and arbitrarily assumed to be 1.0 m, but the maximum rooting depth of the vegetation or the depth to an impermeable horizon is used if either of these is clearly less than 1.0 m. Available water is thus closely related to the depth of root development, and plants are considerably more susceptible to stress through lack of moisture in the early stages of establishment, when the rooting depth is limited.

The *Soil Moisture Deficit* (SMD) is the cumulative reduction in soil moisture content below field capacity as potential evapotranspiration exceeds rainfall over the summer months. SMD is discussed further in Section 3.4.1. Data on rainfall, potential evaporation and soil moisture deficit can be obtained from the Meteorological Office, and from Hall *et al* (1977), Robson and Thomasson (1977) and Bendelow and Hartnup (1980).



Key: C, clay; zC, silty clay; zcL, silty clay loam; cL, clay loam; scL, sand clay loam; zL, silt loam; szL, sandy silt loam; sL, sandy loam; lS, loamy sand; S, sand.

(a) Air capacity and water retention for a range of soil textures



(b) Soil texture and available water capacity (AWC)

Figure 2.13 *Relationships between soil texture, available water capacity (*AWC*) and air capacity (*AC*) (after Jarvis and Mackney, 1979; Etherington, 1982)*

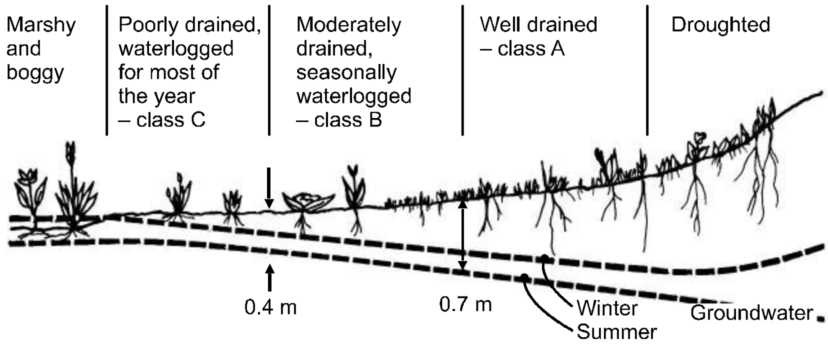


Figure 2.14 *Typical soil wetness classification*

Droughtiness is a characteristic derived from the PAW and the potential SMD, the latter being calculated from potential evapotranspiration and rainfall. It is a measure of the likely intensity of moisture stress which a plant will experience. The soil moisture regime is also influenced by the natural drainage and the variation in the groundwater level, particularly the frequency and duration of waterlogging. A typical soil wetness classification is given in Figure 2.14.

2.4.3 Chemical properties of soil

The soil provides the plant with a chemical as well as a physical environment. The parameters used to define the properties are given in Box 2.7. Major chemical factors which affect plant growth are: pH, plant nutrient concentration and supply, and substances in toxic concentrations. The soil properties which determine or modify these are summarised in Box 2.8.

The pH of many soils lies in the range 5.5 to 7.5, though there are soils outside this, more especially at the acidic end. Excess acidity in soils is one of the most frequently encountered problems, especially when dealing with peaty topsoils or mineral soils and spoils which have developed from acidic rocks.

There are three types of acidity in soil: active, reserve and potential. The *active acidity* is simply the free H^+ ion content as determined by the pH measurement of the soil solution. *Reserve acidity*, which is related to the H^+ ions which are stored on the exchange complex of the soil, determines how much the soil resists changes in pH when a neutralising agent such as lime is added. *Potential acidity* is the acid-generating capacity of the soil due to chemical reactions such as the oxidation of pyrite (FeS_2) to form sulphuric acid. Significant potential acidity is a rare occurrence and would normally only be found in sulphide-rich soils derived from certain geological strata, eg the coal measures and some sandstones which contain iron pyrites.

Box 2.7 *Soil chemical parameters (definitions relating to plant growth)*

Parameter	Definition	Assessment
pH, (soil reaction)	Measure of soil acidity (pH<7) or soil alkalinity (pH>7)	Direct measurement of soil in water suspension using a pH meter
Conductivity, mmho/cm	Content of soluble salts which can be toxic at high levels	Direct measurement of soil in water suspension using a conductivity meter
Total nutrients (nitrogen, phosphorus, potassium, calcium, magnesium), %	Content of all fractions in the soil, regardless of their availability to plants	Laboratory measurement involving digestion with standard extracting solutions
Available nutrients (phosphorus, potassium, calcium, magnesium), mg/kg (=ppm)	Content of fractions easily available to plants using an extractant of similar chemical extracting power to plant roots	Laboratory measurement involving extraction with standard extracting solutions
Mineralisable nitrogen, mg/kg (=ppm)	The quantity of nitrogen mineralisable to plant-available form by micro-organisms	Incubation of sample for 14 days, then extraction of nitrogen
ADAS Index	System used by the Ministry of Agriculture, Fisheries and Food (Agricultural Development and Advisory Service) for available nutrient level.	Extraction using standard ADAS techniques and reference to tables
Cation exchange capacity meq/100g	Ability of soil minerals to absorb charged ions into the surface of soil particles, which might then be available to plants	Laboratory measurement involving saturation with known ion and then extraction
Pyrite, %	Content of active sulphide (usually iron sulphide) which can oxidise in air to produce sulphuric acid. Applies to subsoils and strata of deep origins when they are exposed by earthworks	Laboratory measurement of "active" pyrite

Reference for soil chemical analysis: Allen *et al*, (1974), ADAS (1981)

Box 2.8 *Soil chemical characteristics affecting plant growth*

Important soil characteristics	Principal determinants				Modifiers			
	Particle size	Clay	Organic matter	Parent material	Fertilisers and manure	Rainfall	Vegetation cover	Time
Nutrients			●	●	○		○	
Ion exchange capacity		●	●				○	○
Fixation capacity				●	○			
Leaching	●		●			○		
pH			●	●	○	○		
Toxicities	●			●	○			○

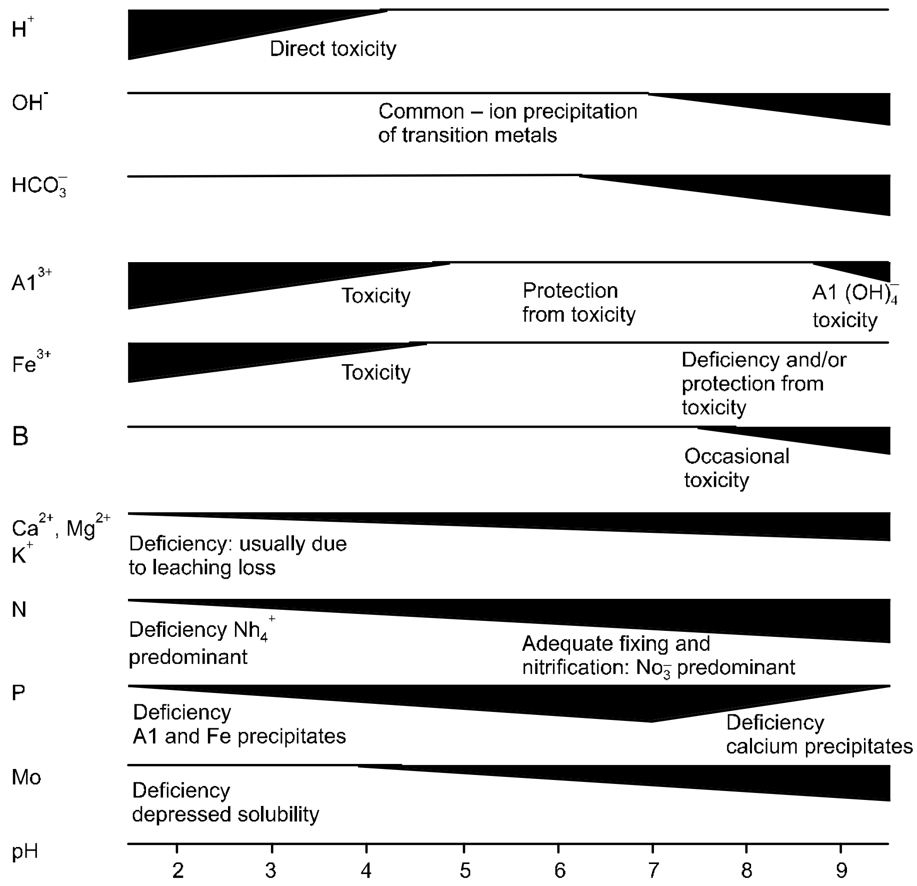


Figure 2.15 *Variation in soil properties and availability of nutrient ions with pH (after Etherington, 1982)*

Alkalinity in soil depends mainly on the content of calcium and magnesium minerals, mostly as carbonates. Soils derived directly from limestone rocks have a naturally high pH of about 7.5 to 8.2. Spoil materials from some industrial processes can also have a high pH. The main significance of soil pH is that it affects the availability of certain minerals, as shown in Figure 2.15. This applies particularly to the availability of essential mineral elements, such as phosphorus, and potentially toxic ones, such as aluminium.

Plants need nutrients which they absorb from the soil via the roots, as shown in Box 2.9. On infertile soils the addition of nitrogen is usually the most significant element controlling plant growth and productivity, but phosphorus and potassium are also important, together with a range of other minerals needed in smaller quantities. Fertilising is discussed in Section 4.2.6. Inorganic minerals are taken up by plants and subsequently returned to the soil as organic matter when they die. Minerals in this organic matter become available to plants again when they are decomposed by micro-organisms. The last process of this cycle is known as mineralisation. In fertile topsoils there is a large amount of organic matter cycling in this way; Figure 2.16 illustrates a typical nutrient cycle and indicates where problems can occur.

Box 2.9 *Mineral nutrients essential for plant growth*

Nitrogen (N) Phosphorous (P) Potassium (K)	Major nutrients, essential in substantial quantities
Sulphur (S) Calcium (Ca) Magnesium (Mg) Sodium (Na)	Minor nutrients, required in small quantities
Iron (Fe) Manganese (Mn) Boron (B) Copper (Ca) Zinc (Zn) Molybdenum (Mo)	Trace minerals, required in very small quantities for healthy growth

Note Mineral nutrients are sometimes referred to by their oxide, ie Phosphate (P_20_5), Potash (K_20), CaO and MgO. Fertilisers are usually given as the proportion (%) by weight of N: P_2O_5: K_20, eg 20:10:10 contains 20% nitrogen, 10% phosphate (about 4.3% phosphorus) and 10% potash (about 8% potassium).

The lack of available nutrients in infertile soils such as subsoils and mine spoils results in poor plant productivity and function. Management of these soils so as to encourage the development of a self-sustaining nutrient cycle is vital, and can take several years.

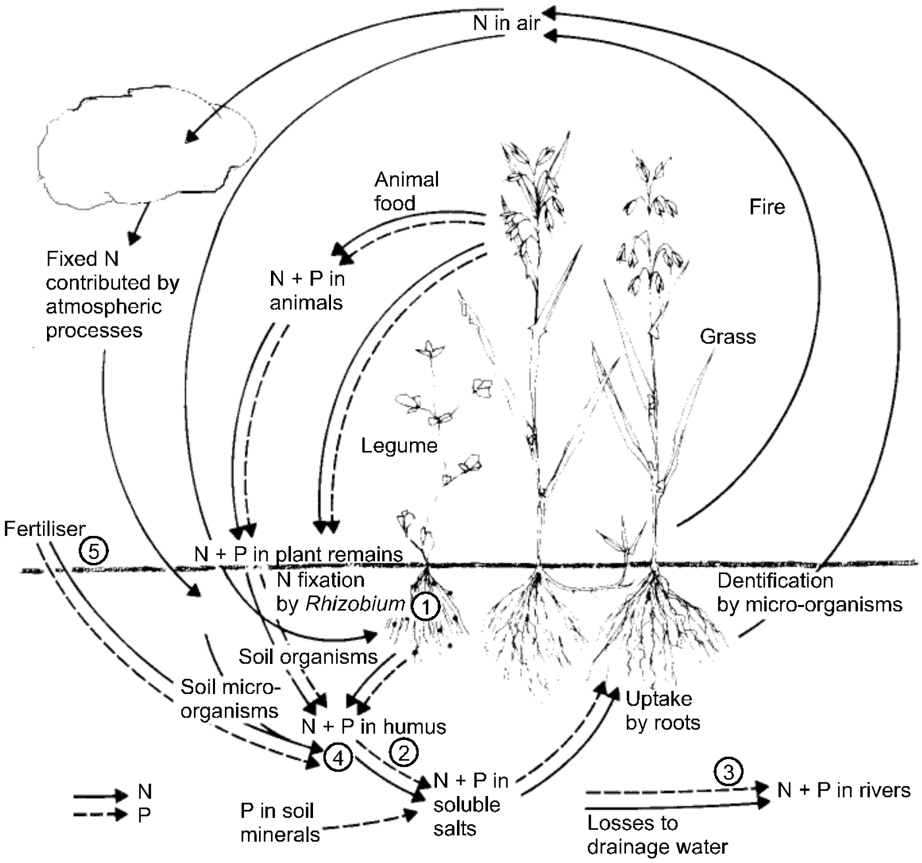
Plant nutrients such as ammonium, potassium and calcium are found as free ions in the soil water, or bound by electrical and chemical bonds to the soil particles. The ability of a soil to yield bound ions is called the *exchange capacity*. As these bound ions are less easily leached than those in solution, the exchange capacity is an important factor in determining the fertility of a soil. The exchange capacity of a soil is largely dependent on its clay or humus content. A coarse-textured soil with a low humus content will therefore have a much lower capacity to store and supply plant nutrients than one with a high humus or clay mineral content.

Toxicity is uncommon in soils unpolluted by man. Some soil strata and spoil materials such as colliery spoil, pulverised fuel ash (PFA) and metalliferous mine wastes can contain elements, mainly metals, which are toxic to plants. Man-made pollution which affects plant growth includes contamination of air, soils and waters with spilt oils and fuels, industrial discharges, landfill leachates, sulphur dioxide and sewage effluent.

One frequently-encountered form of toxicity is due to a high salt content, mainly sodium chloride. This is rare in natural soils in the UK, except around the immediate coastal fringe, but is associated with particular environments, such as roadside verges, and can also result from persistent irrigation.

Specialised plants can grow in soils directly affected by salt, and only in very extreme cases is the salt content actually toxic. Salt is easily washed from the soil and so does not persist or accumulate. Salt in spray drift will affect plants at greater distance from the source, scorching leaf growth, and may eventually kill the plant if it is heavy or persistent.

Soil fertility is a complex interaction of all the above factors. Soil nutrients can be provided by using fertilisers or manures but, in the interest of long-term economy, it is necessary for the soil/plant system to be managed so that fertility becomes largely self-sustaining.



N = Nitrogen

P = Phosphorus

Where problems can occur in the cycle:

1 Nitrogen fixation by *Rhizobium* bacteria in legume roots can be inhibited by low pH or nutrient deficiency. Legumes may not be present in the sward.

2 Release of nutrients in organic matter by micro-organisms may be inhibited by low pH or a high carbon : nitrogen ratio in the organic matter. If release is blocked, humus will accumulate and the minerals become locked up and unavailable.

3 In areas of high rainfall and/or porous soil, many soluble minerals will be quickly leached away.

4 The organic matter/humus store can be very small in "young" soils, so that the amount of nutrients released by micro-organisms can be almost insignificant.

5 Fertiliser inputs are essential in the early years; this will be the only source of nutrients until the humus fraction has built up sufficiently for natural cycling to be adequate.

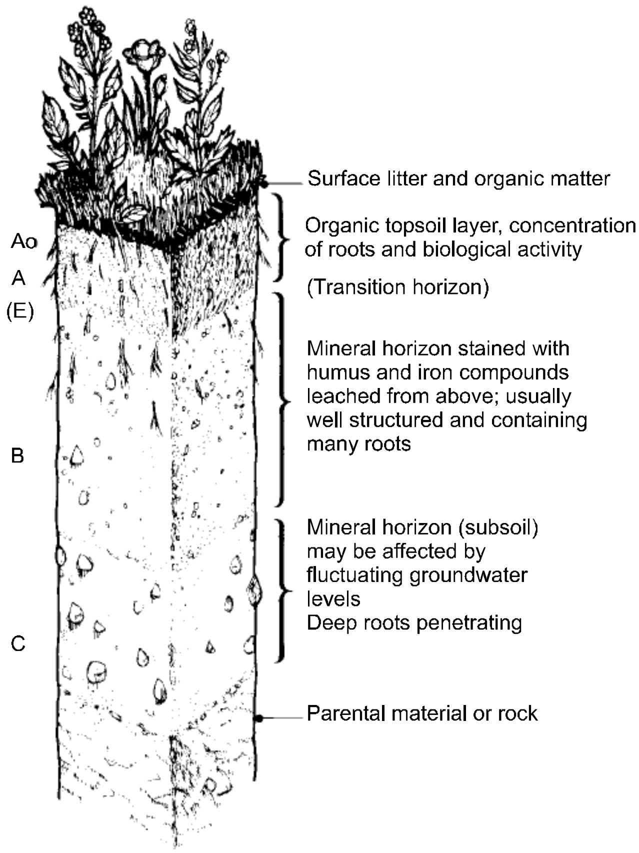
Figure 2.16 *Typical nutrient cycle for N and P and the problems that can occur in infertile or hostile soils (after Bradshaw and Chadwick, 1980)*

2.4.4 Soil horizons

In civil engineering, topsoil is defined as the upper humic part of the soil profile, as shown in Figure 2.17. This is the A horizon, as recognised by the soil scientist, and is not simply a single layer above the subsoil. The process of soil formation gives rise to a number of discrete but integrated horizons, the nature and properties of which are determined by the parent material and the development process under a particular vegetation type and climatic regime. The topsoil and subsoil horizons should be examined carefully and described fully in all site appraisals and investigations. Ideally a specialist soil surveyor should advise on the removal, storage and handling of soil as well as on its physical characteristics. This topic is discussed further in Section 4.2.

Many subsoils and mine spoils can support adequate vegetation, and with careful management will eventually become good topsoil material. It is not necessary to specify topsoil as the surface finish in every situation.

Figure 2.17 *Typical topsoil profile*



The extent, nature and properties of each horizon are determined by the soil parent material and the soil development process, under a particular vegetation type and climatic regime. Subsequent management or interference by man will substantially modify the profile.

2.4.5 Soil potential

The physical, water and chemical characteristics of the soil can be combined into an overall assessment of soil potential for plant growth. A scheme for this is given in Box 2.10.

Box 2.10 *Assessment of soil potential*

Class A is the highest quality and suitable for situations where good quality fertile topsoil is necessary. However, class C, whilst of poorer quality, would still be suitable for many situations (*see* Section 4.2.1). In many cases it would be possible to modify or manage a class B or C soil to improve its quality.

Parameter	*Unit*	*Suitability class*			*Unsuitable*
		A	*B*	*C*	
Soil type					
Texture	description[1] and clay%	fLS,SL SZL,ZL	SCL,CL, ZCL,LS	C<45% SC,ZC,S	C>45%
Stoniness	% vol	<5	5-10	10-15	>15
Available water capacity (at packing density 1.4-1.75)	% vol	>20	15-20	10-15	<10
pH		5.7-7.0	5.2-5.5	4.7-5.5	<4.7
			7.0-7.3	7.3-7.8	>7.8
Conductivity	mmho/cm	<4	4-8	8-10	>10
Pyrite	% weight	–	<0.2	0.2-3.0	>3.0
Soil fertility					
Total nitrogen	% weight	>0.2	0,05-0.2	<0.05	
Total phosphorus	mg/kg	>37	27-37	<27	
Total potash	mg/kg	>360	180-360	<180	
Available phosphorus	mg/kg	>20	14-20	<14	
Available potassium	mg/kg	>185	90-185	<90	

Notes: 1 _ f = fine, S = sand, C = clay, L = loam, Z = slit

Such a scheme can be used in several ways:

- to select suitable soil materials for use as a surface covering in which to establish vegetation (*see* Section 4.2.1)
- to determine how the soil should be placed and cultivated, and, for example, its optimum density requirements
- to design a soil profile to suit the site and vegetation required (*see* Section 5.4.1)
- to predict the potential plant productivity and performance
- to establish the necessary management regime needed to maintain the required plant performance and function.

Soil suitability and potential for a range of specific purposes are discussed more fully in Jarvis and Mackney (1979) and other publications on soil use and management (such as Russell, 1973).

2.5 Plants and climate

The climatic factors which affect plant behaviour and performance, comprising growing season, moisture regime, exposure and rainfall seasonality, make up the bioclimate. The main parameters of the bioclimate are summarised in Box 2.11. Bioclimatic classifications are published by the Soil Survey of England and Wales and the Soil Survey of Scotland, and are given in Box 2.12. The maps give a useful guide to regional conditions.

Box 2.11 *Bioclimate: parameters and definitions*

Rainfall, (mm)	Precipitation recorded on daily basis and compiled monthly, seasonally, yearly or for long-term averages
Potential evapotranspiration, E_t (mm)	Estimated water loss from a grassed surface calculated from records of sunshine, temperature, wind and humidity
Rainfall erosivity, R	Estimate of the power of rainfall to erode soil, based on records of intensity and rainfall energy
Growing season	An estimate of the length and intensity of the growing season, based on the accumulated average daily temperature above 5.6°C
Exposure	Relative elevation and aspect

Bioclimatic factors are estimated from long term meteorological data.

Sources of climatic/bioclimatic data

1 The Meteorological Office produces statistics for rainfall, wind, E_t, soil moisture deficit, temperature, etc., as long term averages or over specific periods for the whole of the UK.

2 The Ministry of Agriculture, Fisheries and Food publishes long term data for agricultural climate and for drainage and irrigation design (Smith, 1976).

3 The Soil Survey of England and Wales (Bendelow and Hartnup, 1980) and The Macaulay Institute for Soil Research in Scotland (Birse and Dry, 1970; Birse and Robertson, 1970; Birse, 1971) publish maps of bioclimatic parameters and maintain detailed climatological records.

4 Standard text books such as Chandler and Gregory (1976).

Box 2.12 *Bioclimatic classification of the UK (after Bendelow and Hartnup, 1980; Chandler and Gregory, 1976)*

1 Thermal regions

Symbol	*Description*	*Accumulated temperature (day °C>5.6)*
A	Moderately cold	825
B	Slightly cold	825—1375
C	Moderately cool	1375—1650
D	Moderately warm	1925

2 Moisture regime

Symbol	*Description*	*Moisture deficit, mm (annual)*
1	Moderately wet	<40
2	Slightly wet	40—60
3	Moderately moist	60—100
4	Slightly moist	100—180
5	Slightly dry	>180

3 Rainfall seasonality

Symbol	*Description*
w	Areas with a rainfall maximum in the winter half of the year
2	Areas in which the maximum is during the second half of the year
s	Areas where there is a slight tendency for a summer rainfall maximum (in the UK mainly East Anglia and Thames Valley)

4 Exposure categories

Symbol	*Description*	*Approximate mean annual wind speed (m/s)*	*Vegetation effect*
m	Unexposed	<4.8	Tree growth moderate to good
p	Exposed	4.8—6.6	Tree growth poor
v	Very exposed	>6.6	Heather very short, trees absent

5 Growing season

A	9 or more months
B	7 – 8 months
C	5 – 6 months
D	4 or less months

The overall bioclimate, which can be estimated from local or regional long-term averages, will be considerably modified by local conditions, particularly topography. The effects of slope angle and aspect are outlined in Box 2.13, and other factors such as exposure, summarised in Box 2.14, should be assessed critically on site. As altitude increases, growing seasons are shorter, temperatures lower and rainfall generally higher. Standard altitude adjustments are published for most climatic variables in the UK. Figure 2.18 illustrates a typical average monthly moisture regime for lowland Britain.

Bioclimatic factors can be used to assess the overall site potential for plant growth. A suggested scheme is given in Box 2.15.

Box 2.13 *Effect of slope angle and aspect on bioclimate*

The effects of aspect, especially at steep slope angles, significantly modify local climate in two important respects:

1) Solar radiation input.
2) Windspeed and direction, in relation to the local prevailing winds.

These in turn affect the local bioclimate at the ground surface and modify:

1) The beginning, duration and end of the growing season.
2) Potential evapotranspiration and thus soil moisture balance, particularly the intensity of drought.
3) The diurnal temperature fluctuations.
4) Exposure.

There are a few empirical studies of some of the effects, but no sufficiently comprehensive models which can be used to predict their likely extent or intensity with respect to the "normal" data for a horizontal surface. Estimating the effect of local variation of slope is therefore a subjective judgement. Some general guidelines are given below.

Season	***Southerly aspects****	***Northerly aspects****
Winter	Wide range of diurnal temperature variations with regular freeze-thaw cycles	Narrow range of diurnal temperatures stays frozen/cold. Snow cover protects vegetation from exposure
Spring	Rapid warming of soil, early start to growing season. Early spells with soil moisture deficit (SMD)	Delayed growing season but very rare to experience SMD
Summer	Extreme surface temperatures and very high SMD for extended periods	Moderate surface temperatures, may avoid prolonged SMDs
Autumn	Growing season extends into cooler months. SMD takes longer to be reduced by rainfall	Early end to growing season, early end to SMD

Seasonal prevailing wind conditions should also be taken into account.
The angle of south facing slope receiving maximum solar radiation input:

Winter	75° from horizontal
Spring/autumn	55° from horizontal
Summer	30° from horizontal

* The effect of other aspects will be intermediate between north and south

An important link between the climatic elements of temperature and rainfall and plant performance is provided by transpiration. This is the vital process by which moisture and nutrients are transferred upwards from the soil to the aerial parts of the plant, and its rate is dependent on the rate at which water evaporates from plant surfaces. The pattern of evaporation of water throughout the year is a characteristic of a climate, but plants can to some extent control the rate at which water evaporates from their surfaces, and thus the combination of transpiration and evaporation has an important bearing on plant physiology.

Plant survival depends on an adequate water supply and, where new vegetation is to be established, the expected water requirement may have to be considered in order to assess the water input required to balance the evapotranspiration that will occur. Evapotranspiration is discussed in greater detail in Section 3.4.

Box 2.14 *Exposure: local assessment (after Miller, 1985)*

The degree of exposure is a relative factor, and can be assessed subjectively on a simple scale (as in the exposure categories of the bioclimatic classification, Box 2.12). A more objective assessment can be based on the TOPEX score, determined as follows.

Topography factor Measure the angle of inclination to the horizon at the eight major compass points. Add together those where inclination is above horizontal, and subtract those below.

Windiness factor Wind zone scores are given for each wind zone in the UK.

Wind zone	A	B	C	D	E	F	G
Score	13	11	9.5	7.5	2.5	0.5	0

Elevation factor

>540 m	score 10	315–360m	score 6	191–225m	score 2
466–540	9	286–315	5	141–190	1
406–465	8	256–285	4	61–140	0.5
361–405	7	226–255	3	60	0

Sum the scores for the three factors to give a total TOPEX score from which the exposure category is determined:

		TOPEX
1	Severely exposed	10
2	Very exposed	11–30
3	Moderately exposed	31–60
4	Moderately sheltered	61–100
5	Very sheltered	>100

Wind zones in Britain

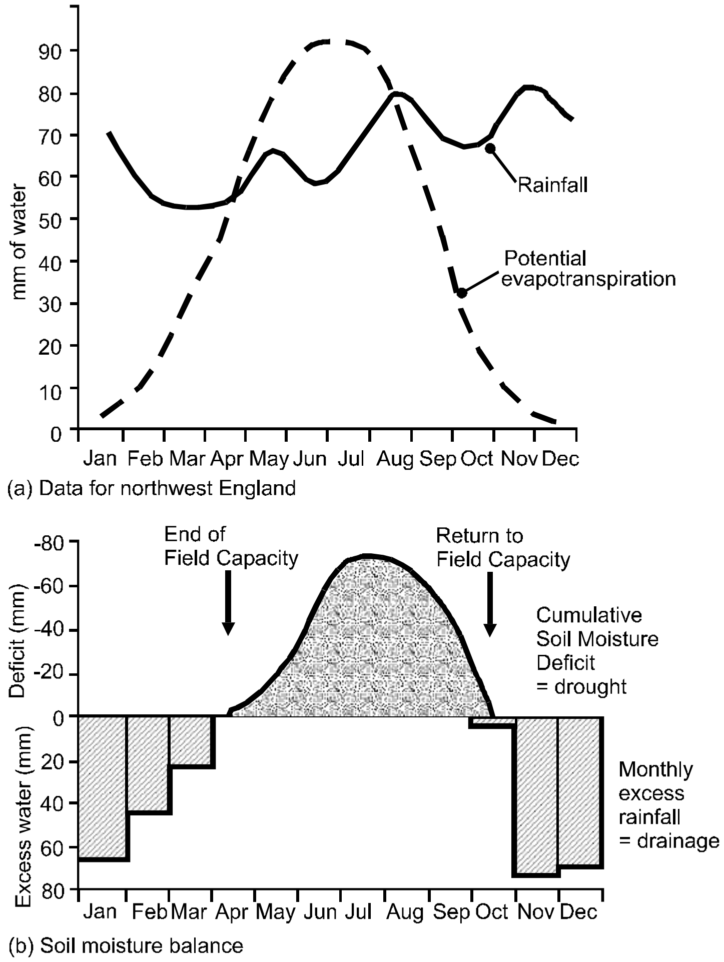


Figure 2.18 *Typical average monthly moisture data*

Box 2.15 *Site assessment of bioclimatic potential for plant growth*

	Classes[1]				
Factor	1	2	3	4	5
Thermal region[2]	E	D	C	B	A
Moisture regime[2]	2	2	3	4	5,1.
Growing season[2]	A,B	B	B/C	C	D
Exposure, TOPEX[3]	5	4	3	2	1

1 The classes range from 1 = best, most favourable
to 5 = worst, least favourable.
The overall class appropriate to any site should be based on an Interpolation average of the classes for each factor.
2 Classification given in Box 2.12.
3 Classification given in Box 2.14.

2.6 Plant propagation

Plants reproduce by two mechanisms:

1 Seed production.

2 Vegetatively, for example by runners, suckers or buds.

Many species use both methods to varying extents, depending on their strategies for dealing with stress and disturbance (*see* Section 2.2.4). Man has adapted both reproductive mechanisms to his own use, and has added a few others, including the taking of cuttings, layering and tissue culture. There are three widely used techniques of propagation appropriate for engineering and landscaping: direct sowing, planting nursery-raised plants and planting cuttings. The latter two techniques are generally used for trees and shrubs. In each of these cases the establishment period is critical because the individual plant is at risk from many sources, such as drought, predation and damage.

2.6.1 Seeding

Plants vary in their seed production strategies. Some, such as many grasses, produce a large quantity of very small seeds, each of which has only a small food supply. Small-seeded plants are often susceptible to desiccation early in establishment. Others, for example some trees, produce a smaller quantity of large seeds, each with a fairly large food-store. Establishment of large-seeded plants is often good but the seeds themselves can be subject to predation.

The establishment phase has three stages:

1 A period for the dormancy to break. This may simply involve the seed absorbing sufficient water for metabolism to begin. Many plants have elaborate dormancy mechanisms, however, including a requirement for a cold period and periods of either light or dark.
2 Germination of the seed, where the seed coat splits and the young root emerges and penetrates the soil. Adequate moisture is essential for good germination.
3 Establishment of the young plant in a favourable environment.

Moisture is the most critical factor during these stages. If the seed is unprotected, the chances of its drying out before the root grows to sufficient depth in the soil are quite high. Protection can be provided by covering the seed with a mulch or a thin soil layer, or by preparing a roughened surface so that the seed falls down a crack or crevice where establishment conditions are likely to be favourable.

2.6.2 Planting

A plant which is transplanted will inevitably suffer disruption of its root system. Different types of root systems (*see* Section 2.1.5) respond differently to transplanting. Fine fibrous roots are easily damaged and can quickly dry out when exposed to the atmosphere. Root regeneration can therefore be slow if transplanting is not carried out carefully. Large fleshy roots are more resistant to desiccation and therefore regenerate more readily. If a root system is severely damaged, such as the taproot being severed, it may remain stunted, and the plant suffers accordingly. As a general rule, the younger that a plant is transplanted, the more successful the root system.

The availability of water in the period immediately after planting is critical. The material into which a tree or plant is planted must allow water to move freely and must have sufficient moisture-holding capacity.

2.7 Reliability and variation

Reliability and variation in vegetation growth and persistence are factors which will be of particular interest to engineers considering its use in permanent works. The topics should be considered from two standpoints:

1 Reliability and variability in plant material.
2 Reliability and variation in site conditions.

Vegetation is a living material and is subject to natural inherent variability and sensitivity to environmental changes. Nevertheless, enough is known about plants and plant behaviour in almost any given set of circumstances to enable reasonably reliable predictions of performance to be made. Furthermore, if these circumstances change as a result of natural events or human interference, it is quite possible to predict in general terms what the consequences of these changes for the vegetation are likely to be.

Individual plants may have a finite life but plant communities can last indefinitely if they are in equilibrium with their environment. This applies both to natural communities, such as ancient woodland, and man-made types, such as coppiced woodland or permanent pasture. Change or unreliability occurs as a result of changing circumstances or very occasional natural catastrophes.

Difficulties can arise when vegetation has to be established, or re-established on bare soil, and it is at this point that experience and knowledge in agricultural systems differs from that in construction. The most important and fundamental requirement in any system based on vegetation is to understand the soil/plant relationships. A farmer achieves this by long experience of working in a particular location and an appreciation of the limitations imposed by external factors such as climate. Failure in this respect was found to be the underlying cause for problems experienced in Wales in establishing vegetation as part of road improvement schemes. The Welsh Office Highways Directorate undertook a study of vegetation failures on highway margins, as summarised in Box 2.16, and concluded that, given the site conditions, the poor performance by the vegetation was predictable, and that the seed mixtures sown had little opportunity of doing any better.

Left to its own devices, the species composition of a plant community will be subject to changes due to natural weather cycles, or to randomly occurring events which cause specific damage. The extent and effect of these changes, which are discussed below, are bound to influence the performance of vegetation but, with the right vegetation established in the right place and maintained in an appropriate manner, these uncertainties can be reduced in number and degree.

Box 2.16 *Vegetating unstable and unsightly slopes on highway margins*

The Welsh Office Highways Directorate has studied the role and performance of vegetation in providing shallow-seated stability and preventing erosion on highway margins in Wales. The study was prompted by the seemingly poor performance of vegetation in many areas, which contributed to the creation of landscape scars and a maintenance burden due to the continual slippage of material.

The study was in two parts:

1. Characterisation of the physical, chemical and biological attributes of slopes with a history of poor vegetation cover and erosion problems.
2. Investigation of species, seed mixtures and methods of treating these slopes to overcome the problems.

Interim results indicate that:

1. Interaction between geology, climate and design are important in determining the type of vegetation which develops on slopes.
2. Acidity of the soil and altitude of a site are important in determining species survival.
3. Of the seed mixtures sown on the sites surveyed, the only component found some years after sowing was Red Fescue, indicating that a better match is required between site conditions and plant selection.
4. Vegetation cover is directly related to the proportion of material smaller than 2 mm in the soil. Ways of increasing this fraction within the soil or of mimicking its properties, such as water retention, could ensure greater success in establishment. The retention of weathered material would be improved by creating benching or ledges, or by using geotextiles and mulches.
5. Uncontrolled grazing had an adverse effect on vegetation establishment and growth.
6. The active erosion zones which tend to form at the junction between man-made and natural slopes can be removed successfully by reprofiling, as shown in Plate 2D.

Plate 2D *Trial of vegetative slope stabilisation on a highway cutting. Experimental panels in the foreground, with a typical untreated slope in the background. Sheep have been introduced into the lower half of the trial to assess the effect of grazing*

2.7.1 Natural cycles

The performance of vegetation over a number of years and through climatic cycles can be affected by extremes of climate. A sequence of cold winters, or late starts to the growing season, may reduce the frequency of some species in a plant community, allowing others to increase. Similarly a sequence of drought years will affect the rooting pattern and establishment success of some species, as shown in Figure 2.19. Both cold and drought affect growth and this will be important where tolerance to wear and good repair capacity are important. It is difficult to predict when these cycles will occur and how severe they will be. Meteorological data will give some indication of the spread of climatic variables around the mean values, and an indication of the likely range of conditions to be expected.

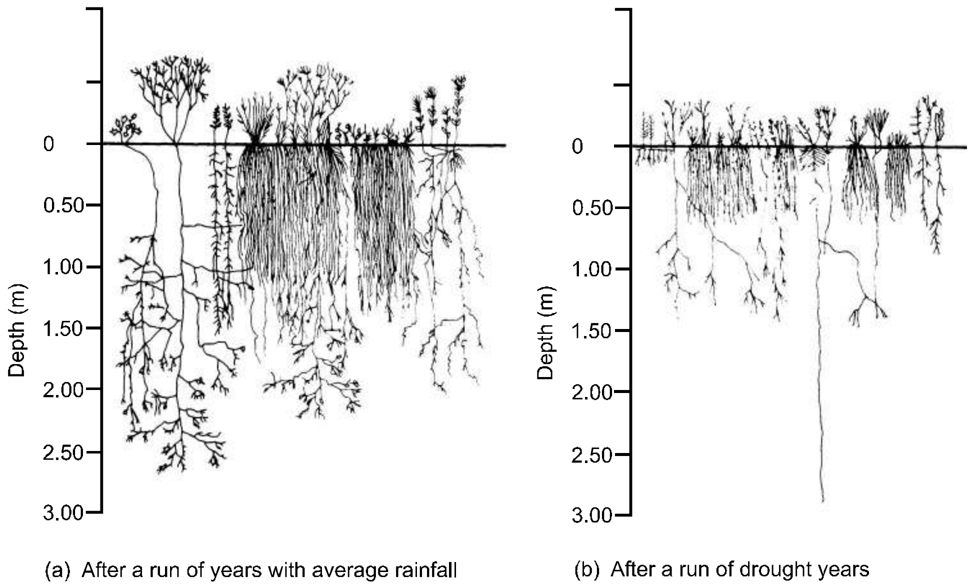


Figure 2.19 *Root systems of a typical short-grass/herb sward showing variation in depth and density resulting from natural climatic cycles (after Russell, 1973)*

2.7.2 Damage

The most common causes of lasting damage to a vegetation cover which may affect its reliability are: extremes of climate, wear, fire, windthrow of larger trees, grazing by stock or wild herbivores, vandalism, pollution, and natural causes (old age, disease). In any application of vegetation, it is prudent to consider the likely impact of its complete removal, whether this is by accident or design. Box 2.17 summarises the possible approaches to assessing the risk of damage occurring, and the measures which can be adopted for protection.

Box 2.17 *Specific risks of damage to vegetation cover*

Cause	*Prediction of risk*	*Protection measures*
Windloading	Windthrow hazard assessment, involving consideration of windiness, exposure, soil type and available rooting depth	Deep drainage to lower water table and encourage deeper rooting Avoid exposed plantation edges; dense stands of trees give mutual protection
Fire	Combustibility of vegetation, especially during the dry season. Resinous plants such as evergreens are generally more combustible	Encourage rapid superficial burn in which roots and stumps are left unaffected to regrow and sprout again Limit area which can burn by splitting up with discontinuities, eg rides or unvegetated strips Plant proportions of species with green, low combustible foliage Consult the fire brigade
Grazing and browsing (stock or wild herbivores)	Adjacent land used for grazing stock Suitability of habitat for wild animals eg rabbits, deer	Protective fencing, regularly maintained Use plants unpalatable to stock Pest control
Natural causes	Life expectancy of plants Disease resistance	Management to encourage natural regeneration Disease control (eg fungicides, insecticides) for specific outbreaks Avoid monoculture of species and age classes as far as possible
Climatic extremes (wet, drought)	Meteorological records Specific site factors which modify general climate, eg aspect, frost pockets	Avoid sensitive species especially in monocultures, use those with known high tolerance of specific conditions Provide shelter from adjacent structures or planting Mulching
Wear	Type and intensity of use Proximity to heavily trafficked areas	Fencing to exclude use Increase soil fertility to encourage vigorous growth and regeneration Reinforce soil surface Use wear-tolerant species
Vandalism	Proximity to urban areas Accessibility to areas of public access	Secure fencing Vigilance and regular maintenance
Pollution	Testing of soil, water, air for toxic chemicals Proximity to potential sources, eg salt water spray at coast and verges on roads subject to salting	Tolerant species

Climatic extremes may eliminate species that are at the limit of their tolerance range. The effects are more marked in monocultures and less so in a diverse plant community where a wide range of species gives resilience.

The most common causes of *wear* on vegetation are excessive trampling by humans or animals, and vehicle pressure. Wear affects plant productivity and species composition, and causes the soil to become heavily compacted and nutrient and moisture regimes to change (*see* Section 6.7). This modifies the engineering properties of the vegetation and, in some cases, causes loss of vegetation and initiates erosion.

The extent of damage caused by *fire* depends on its temperature and frequency. Fire temperature is affected by moisture conditions, the extent to which litter has accumulated on the surface, and vegetation type. Hot fires can kill off roots and underground regenerative parts. On the other hand, plants with growing points at or near ground level, or which can regrow from roots, can to some extent withstand fire.

Some types of vegetation are managed by regular burning, to ensure a cycle of regeneration and to maintain a sub-climax by eliminating young shrubs and trees (*see* Section 2.2.3). Specific examples of this are heathland and grassland. Burning is carried out at a time of year when the top growth is fairly dry, but the ground is damp enough to prevent deep burning. It used to be a regular occurrence on railway embankments in the UK during the days of steam trains. Railway engineers favoured a grass vegetation cover with a dense growth which burned very quickly and superficially, allowing the sward to regenerate. Lineside vegetation now has a much greater proportion of woody species.

Wind loading is the pressure applied by the flow of air on the above-ground parts of vegetation. It affects larger trees with shallow root systems and may uproot them. Plantations with new edges exposed by felling, for example to accommodate a road or pipeline, present particular problems, since the trees have not naturally developed a root system comparable with that of the original edge trees to resist the stresses involved. However, a single tree blowing over in an otherwise dense stand is not usually a cause for concern. The destabilising effect of windloading on trees sufficient to trigger slumping of the soil is more important (*see* Section 3.5.5).

Grazing can fundamentally affect the growth and development of a herbaceous sward (*see* Figure 2.7). Whether a particular level of grazing constitutes damage or not depends on what form of vegetation is required. Overgrazing will seriously affect a sward, increasing the amount of bare ground and dramatically reducing root growth, as shown in Plate 2E. On the other hand, some occasional or regular grazing generally stimulates the ground-level density of a sward. The management of grass swards by grazing is discussed in Section 4.7.2.

Sheep, goats and deer will strip bark from trees, especially young or newly planted ones. Voles, mice, hares and rabbits can also cause extensive damage when present in large numbers. A tree can usually recover from a certain amount of this type of damage, unless the bark has been stripped completely around the main stem.

Vandalism can be a serious problem, especially in urban areas. Physical damage can include breaking stems from trees, pulling up turf and allowing stock to enter by breaking fences.

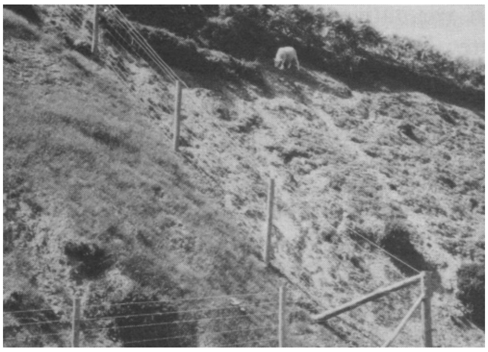


Plate 2E *The effect of overgrazing by sheep on a steep slope; the sward is almost completely denuded*

Pollution may affect specific localised areas as a result of spillages or effluent containing toxic materials. Rivers with poor water quality, due to agricultural pollution, storm sewage overflows or industrial effluent, may only be able to support limited bankside vegetation. Salt pollution occurs immediately adjacent to roads, salt-laden water being splashed onto the verges by passing vehicles. Where it is a regular feature of the environment, salt-tolerant plant species need to be selected (Colwill *et al*, 1982).

Natural causes include a whole range of effects such as old age, disease and pests. Old trees are more likely to be windthrown than young ones. Disease and pests can strike unpredictably, though the risk of severe damage is greatest in old age and in monocultures. Most diseases and pests are species specific, such as Dutch elm disease. Fungal diseases can cause significant damage in grassed areas, especially in mixtures with a limited range of species or cultivars. A high diversity will help to overcome the problems. Highly-bred, artificial varieties tend to be much more susceptible to disease than wild types. Disease infection is often a secondary effect following physical damage such as frost or insect attack, or resulting from poor plant health due to nutrient deficiency.