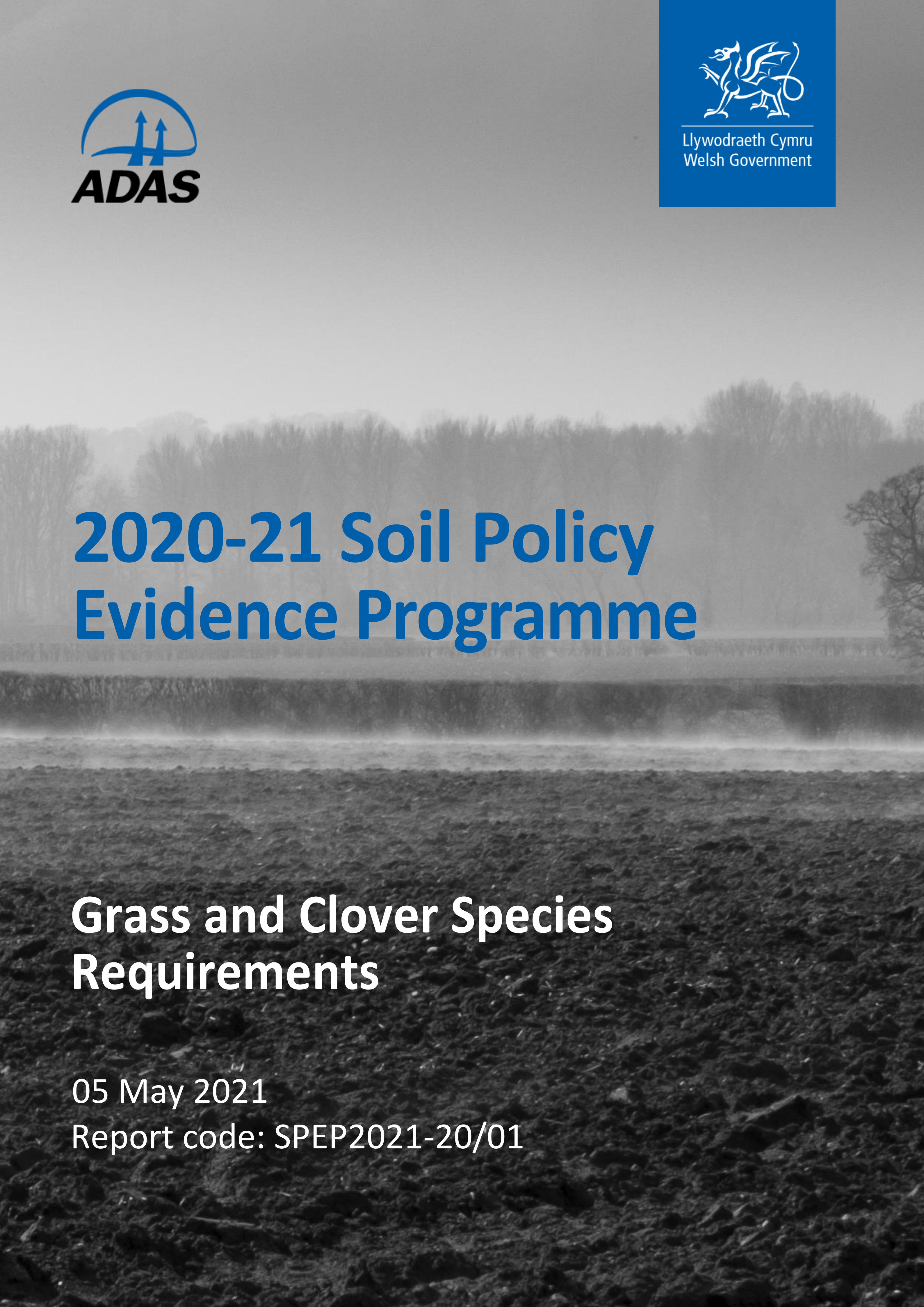


2020-21 Soil Policy Evidence Programme

Grass and Clover Species Requirements

05 May 2021

Report code: SPEP2021-20/01

Llywodraeth Cymru
Welsh Government

Grass and clover species requirements

Submitted to:

Welsh Government
Agricultural Land Use & Soil Policy
Land, Nature and Forestry Division
Department for Rural Affairs

Prepared by:

Dr Alison Rollett
ADAS Gleadthorpe
Netherfield Lane
Meden Vale
Nottinghamshire
NG20 9PD

John Williams
ADAS Boxworth
Battlegate Road
Boxworth
Cambridgeshire
CB23 4NN

05 May 2021

Contents

1 Introduction

- Welsh agriculture is dominated by grassland (permanent pasture, rough grazing and temporary grassland) which can be either improved, natural or semi-natural with contrasting management (i.e. stocking rate and cutting regime). In 2018, of the 1.9 million ha agricultural area in Wales, 89% (1.7 million hectares-ha) was grass, comprising 1.1 million ha of permanent pasture (of which enclosed semi-natural grassland has been estimated to cover 25-30,000 ha (NRW, 2016)), *c*.430,000 ha of rough grazing and *c*.154,000 ha of temporary grassland (i.e. under 5 years old) (Welsh Government, 2019).
- Intensive grassland systems in the UK are currently associated with the widespread use of monocultures (usually perennial ryegrass *Lolium perenne* L.) or binary mixtures that include a legume (usually White Clover *Trifolium repens* L.) (Marshall *et al*, 2016). These swards have a high yield potential and feeding value, can sustain frequent harvesting and/or high stocking rates, and are maintained by moderate-to-high levels of nitrogen (N) input (Wilkins *et al*. 2002).
- In England and Wales, an estimated 97% of unimproved grassland was lost between 1932 and 1984 (Fuller, 1987). The decline was largely attributed to the intensification of agriculture and abandonment of remaining semi-natural grassland areas, which occurred during and after the Second World War.
- This work follows on from work previously completed for Welsh Government, as part of the Capability, Suitability & Climate Programme (CSCP), which considered the climatic, site and soil requirements of *c*.120 crops (ADAS, 2017; ADAS, 2019). The wider CSCP identified drought as a future risk to crop production in Wales due to decreased summer rainfall coupled with increased temperature.
- Further work on the requirements of grass and other forage requirements was requested by stakeholders including farmers, HCC, farming unions and land management organisations. This report is the first part of a wider project that will assess the effects of climate change on grassland productivity and the potential impacts on grass-based agricultural enterprises (dairy, beef and sheep) in Wales.

2 Objectives

- The current climatic conditions in Wales (i.e. warm temperatures and high summer rainfall) are very favourable for grass production for both grazing and cutting. Given the importance of grassland agriculture in Wales it is important to understand the biophysical requirements of the grass and clover species commonly grown. This assessment has considered the climate (e.g. temperature or rainfall) and site limitations (e.g. aspect or gradient) or soil factors (e.g. soil depth, stone content, wetness/drainage or soil pH status) for a range of grass and clover species. In detail the report has:
    - Identified the biophysical requirements of selected grass (i.e. Perennial, Italian and Hybrid Ryegrass, Timothy, Cocksfoot, Bent, Fescue and Yorkshire Fog) and clover species (i.e. Red and White Clover).
    - Identified any changes in the biophysical requirements for different sward mixes (i.e. mixed grass species, clover/grass mixes or forage crop/grass mixes).
    - Assessed the drought tolerance and rooting depth of grass and clover species in relation to the two ALC reference crops of winter wheat and main crop potatoes.

3 Grass growth and yield

- Grass growth starts when soil at a depth of 10 cm reaches 5°C for five consecutive days (AHDB, 2018a). There is variation between grasses, for example, Timothy may start growing at lower temperatures. White Clover and other legumes begin to grow at around 8°C. However, low rates of growth can occur at temperatures down to 0°C, for example, Nagelmüller *et al*., 2016 reported low rates of leaf elongation in perennial ryegrass at temperatures down to 0°C, with an abrupt increase above 5°C.
- A range of factors influence grass yields, including grass species, soil temperature, light, water, nutrient availability and grazing management. Table 1 suggests a typical pattern of grass growth that may be seen in England under moderate nitrogen use, but growth patterns will differ according to soil type, previous management and season (AHDB, 2018). The pattern of grass growth and range of growth (kg dry matter/hectare/day) is likely to be similar for Wales (also see data for Wales in Figures 1 and 2, below).
- Data on grass growth and quality is available online from AHDB (Forage for Knowledge)[1], GrassCheckGB[2] and the Welsh Pasture Project[3] for dairy and beef/sheep farms. The data from these sources report higher average daily growth rates than the AHDB averages (Table 1) but also illustrate the regional (Figure 1) and annual variation in grass growth curves (Figure 2) and monthly dry matter production (Table 2).
- Statistical analysis of the GrassCheckGB data has illustrated the complex relationship between climate and grass growth. The analysis showed that on-farm grass growth rates during 2019 were controlled by multiple meteorological factors. Using univariate regression analysis (i.e. assessing the relationship between individual meteorological factors and grass growth) solar radiation, soil moisture and temperature, average and max/min air temperature and solar energy were all significantly ($P \leq 0.002$) associated with grass growth rates. However, using multivariate regression analysis (i.e. considering all the factors together), only solar radiation and minimum air temperature were significantly ($P \leq 0.003$) associated with grass growth rates. Rainfall and evapotranspiration were not found to be significantly related to grass growth rates either as single factors or as part of the multivariate analysis.

Table 1. Average, minimum and maximum monthly growth (kg dry matter/hectare/day) for grass

Month	Average	Minimum	Maximum
January	0	0	10
February	5	0	10
March	10	0	20
April	25	10	40
May	45	20	60
June	30	20	50
July	20	15	40
August	30	20	50
September	20	10	40
October	15	5	30
November	10	0	20
December	5	0	10

[1] https://ahdb.org.uk/knowledge-library/grass
[2] https://grasscheckgb.co.uk/
[3] https://businesswales.gov.wales/farmingconnect/land/grass/welsh-pasture-project

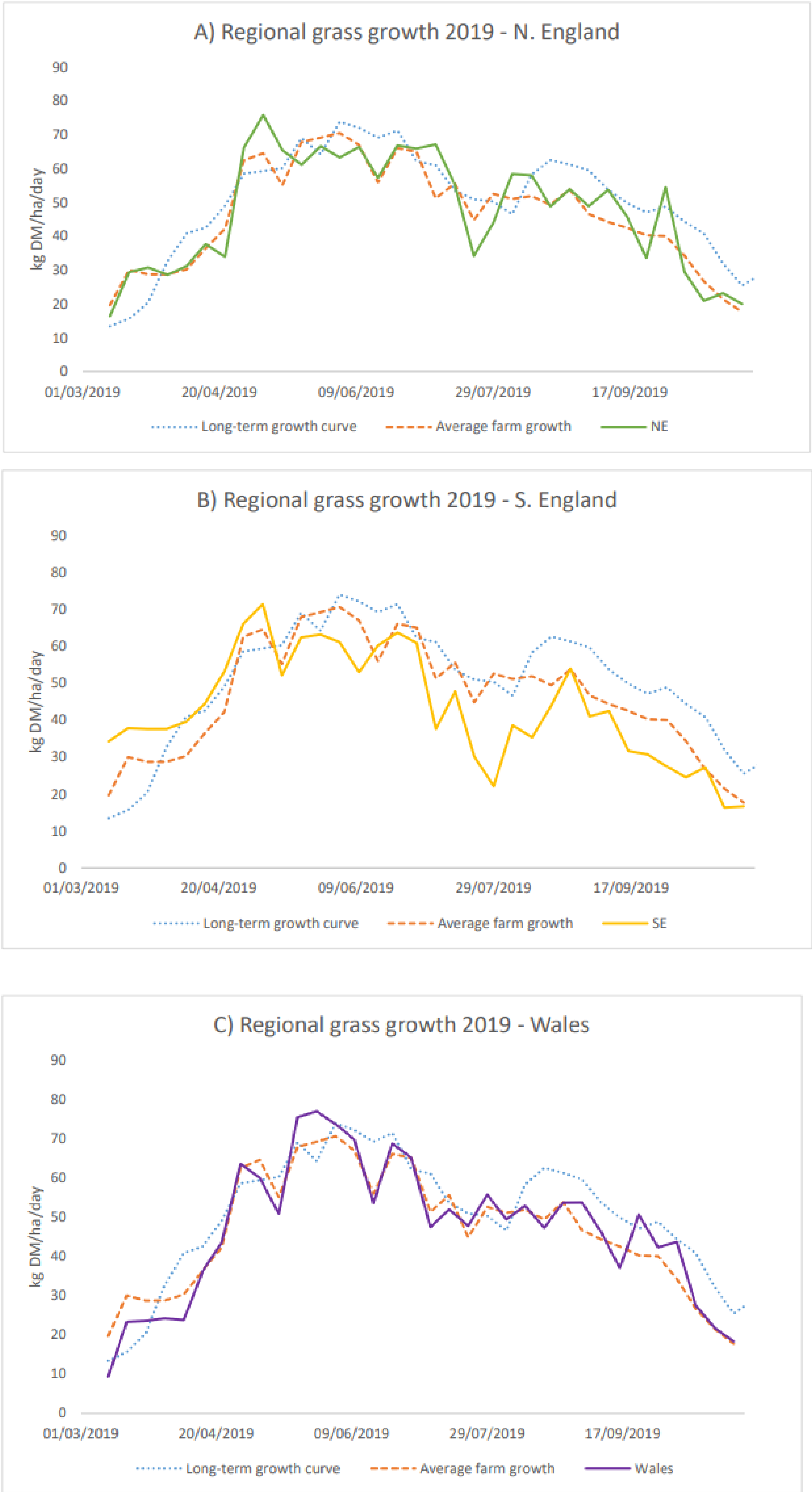


Figure 1. Regional average grass growth recorded weekly in March-October 2019, compared to the average for all GrassCheckGB farms and to the long-term average. A) Northern England (NE), B) Southern England (SE) and C) Wales.

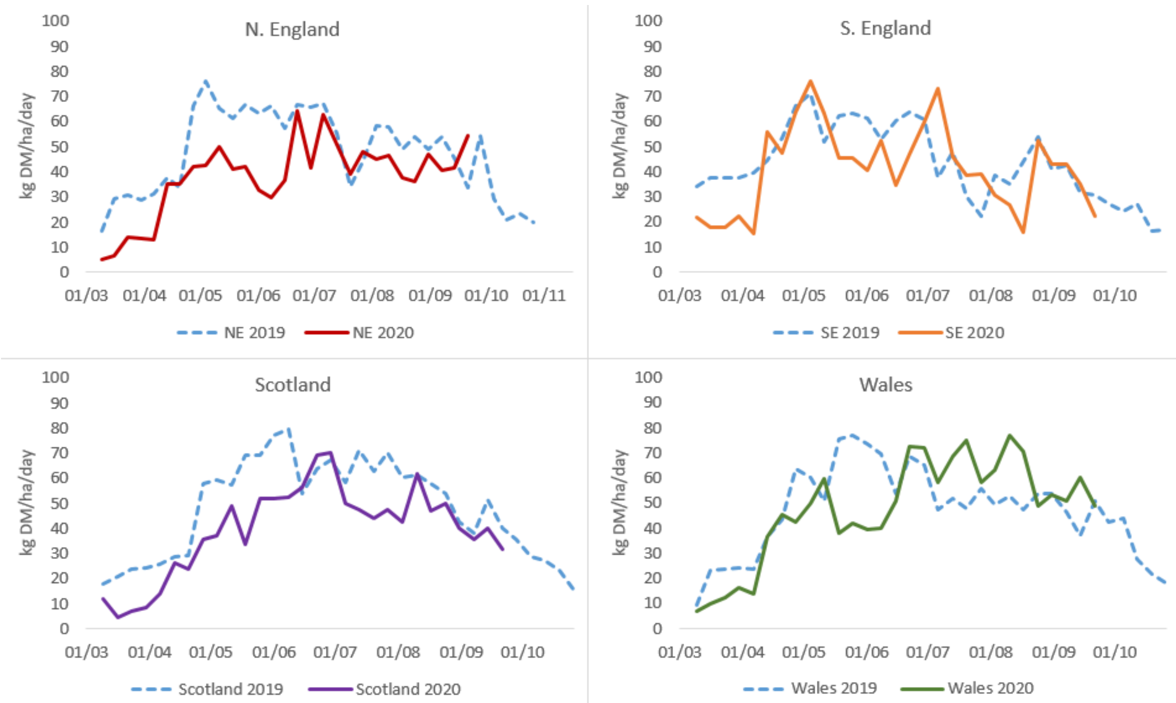


Figure 2. Regional average grass growth March to October 2019 and March to September 2020, for GrassCheckGB farms for Northern England, Southern England, Scotland and Wales.

Table 2. Average regional grass growth rates (kg dry matter/hectare/day) for GrassCheckGB farms in 2019

Month	**Southern England**	**Northern England**	**Scotland**	**Wales**
	kg dry matter/hectare/day			
March	37	26	21	19
April	48	40	33	38
May	62	67	64	64
June	60	64	69	66
July	40	53	66	54
August	43	55	58	51
September	35	47	42	46
October	21	25	24	29

3.1 Species yield and D value.

- The best rated ryegrass, Timothy and Cocksfoot varieties on the Recommended List are capable of grazing (10 t DM/ha) or conservation annual yields more than 15 t DM/ha (British Grassland Society, 2020) whilst weed grasses (e.g. Creeping Bent or Annual Meadow Grass) can yield as little as 2 t DM/ha. Production follows the seasonal growth curves above, peaking in May-July and typically dipping to around one-third of peak levels by early autumn. Some typical yields for a range of grass species are given in the following Table (Table 3).

Table 3. Yield of grass species

Grass species	Annual yield (t/ha dry matter)		
	Cotswold Seeds*	Recommended Grass and Clover Lists 2020-21	
	General	Grazing	Conservation
Perennial ryegrass	13	9.9	15.4
Italian ryegrass	18		17.0
Hybrid ryegrass	14		15.5
Timothy	12	10.2	13.8
Cocksfoot	13		15.8
Meadow Fescue	13		
Festulolium	14-18		

*https://www.cotswoldseeds.com/index.asp

- D value is a measure of digestibility; the digestible part of forage is made up of crude protein, carbohydrates (digestible fibres and sugars) and lipids (oils). ME is the amount of energy that an animal can derive from the grass (MJ/kg DM), 1% D value = 0.16 MJ/kg DM of ME. The D-value is highest in grass when the sward has fresh leafy growth and declines as the plants become more mature (stemmy). The decline in D-value is highest after ear emergence (heading). Grass cut for silage will typically lose 2% D-value between cutting and feeding. The average D value for a range of grass species and types is shown in Table 4, below.

Table 4. Average D-value (%) and [ME (MJ/kg DM)]

Perennial Ryegrass	**Early**		**Intermediate**		**Late**	
	Diploid	**Tetraploid**	**Diploid**	**Tetraploid**	**Diploid**	**Tetraploid**
Grazing	76-77 [*c*.12]	77 [*c*.12]	76-79 [*c*.12-13]	75-79 [*c*.12-13]	75-80 [*c*.12-13]	72-78 [*c*.12-13]
2nd conservation cut	71-72 [*c*.11-12]	71-73 [*c*.11-12]	70-75 [*c*.11-12]	71-76 [*c*.11-12]	72-77 [*c*.12]	72-75 [*c*.12]
Italian Ryegrass	**Diploid**	**Tetraploid**				
2nd conservation cut	66-67 [*c*.11]	67-69 [*c*.11]				
Hybrid ryegrass	**Diploid**	**Tetraploid**				
2nd conservation cut	66-68 [*c*.11]	66-73 [*c*.11-12]				
Timothy						
Grazing	72-75 [*c*.12]					
2nd conservation cut	64-67 [*c*.10-11]					
Cocksfoot	68-69 [*c*.11]					
Red Fescue	61 [*c*.10]					
Creeping Bent	58 [*c*.9]					

3.2 *Grass growth class*

- The grass growth class (GGC) is the ability of site to respond to nitrogen, which depends on soil type, rainfall and altitude (Figure 3). On good/very good GGC sites, swards dominated by productive grass species respond well to increasing N supply, as soil drainage, temperature and water supply are conducive to growth. On poor/very poor GGC sites, grass does not respond as well to N applications because of factors such as poor drainage or cooler temperatures (due to aspect or altitude) (AHDB, 2021).

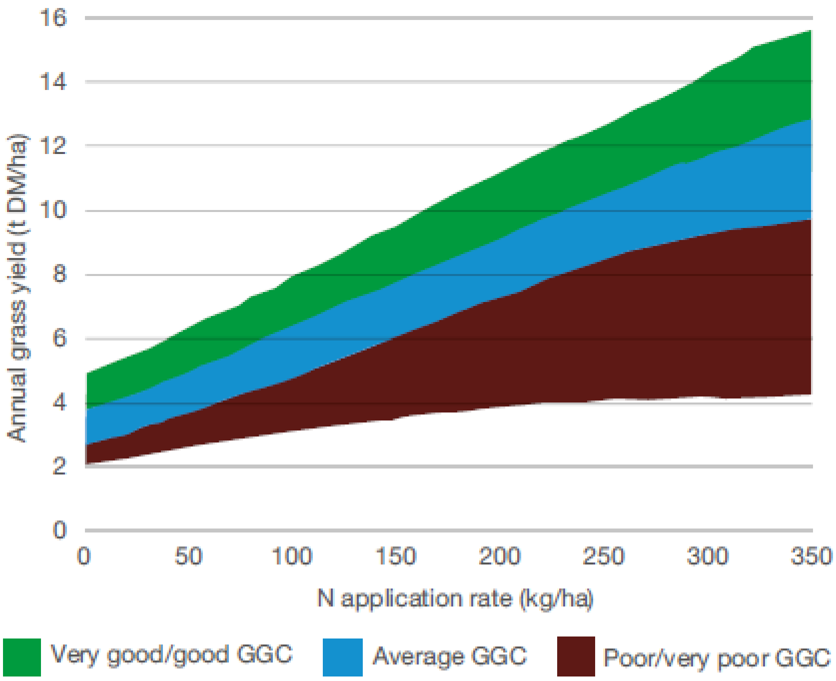


Figure 3. Indicative grass dry matter yield by Grass Growth Class (GGC). Source AHDB, 2021.

3.3 *Recommended Grass and Clover Lists for England and Wales*

- Understanding the performance characteristics of grass and clover allows the selection of species and varieties that will perform well under a particular management system. To help growers select the most appropriate species or variety the Recommended Grass and Clover Lists for England and Wales are published annually (British Grassland Society, 2020). The lists are compiled from data from variety trials carried out by seed companies (e.g. Barenbrug, DLF seeds) and research organisations (e.g. NIAB-TAG, IBERS). Recommended lists, provide information on heading date, grazing and conservation performance, ground cover and hardiness and disease resistance for Perennial Ryegrass (PRG), Italian Ryegrass, Hybrid Ryegrass, Timothy, White Clover and Red Clover varieties. Most research effort by plant breeders has focused on PRG; as a result, PRG varieties dominate the recommended lists (with *c*.80 varieties), compared to, for example, Timothy which has fewer than 10 varieties included in the list.

3.3.1 Heading date

- Grasses are classified according to heading date – which is the date on which 50% of the ears in fertile tillers have emerged. Early varieties of ryegrass reach their heading date in the first two weeks of May; intermediate varieties head during the second half of May and late varieties reach this stage during the first two weeks of June (British Grassland Society, 2020). In general, early heading varieties grow earlier in the spring, are more erect, tiller less freely and are easier to cut for conservation than later heading varieties, which tend to be more prostrate and persistent and give good mid-season growth.

- Early heading varieties produce higher yields in spring, with late-heading varieties having higher yields in summer and autumn (Figure 4), however, there are large differences between varieties (AHDB, 2019).

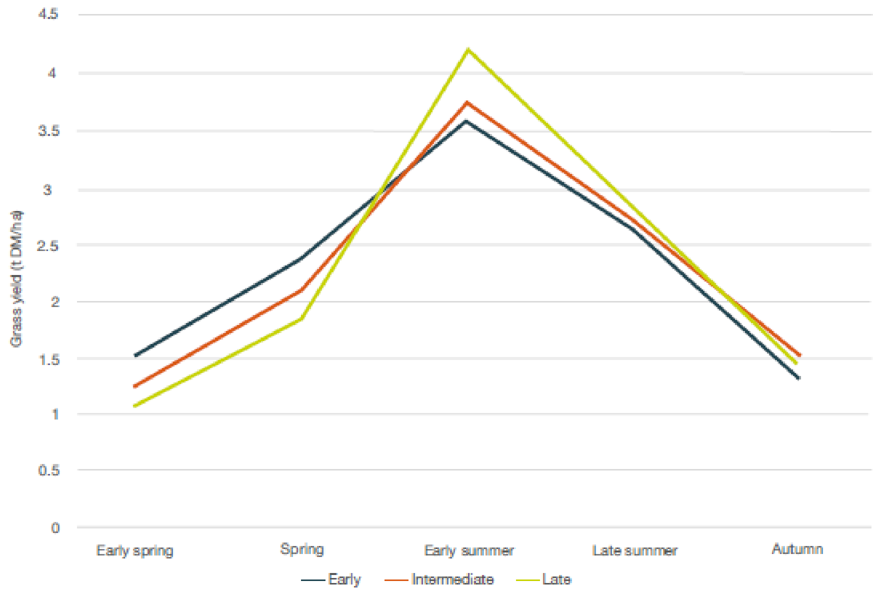


Figure 4. The variation in timing of yields based on heading date.

3.3.2 Diploid and tetraploids ryegrass varieties

- Ryegrasses are grouped into two different types based on their number of chromosomes (ploidy level), Figure 5. For example, the 'Recommended Grass and Clover Lists' for 2020 includes four early diploid PRG (e.g. Genesis) and three early tetraploid (e.g. AberTorch) varieties. There are also 14 intermediate and 23 late diploid PRG varieties and 17 intermediate and 18 late tetraploid PRG varieties. Diploid varieties have two sets of chromosomes (2n = 14) in each cell; their cells are smaller in size with lower water (moisture) content; their plant structures (leaves and seed size) are smaller; and the plants tend to produce more tillers (Lemus, 2017). Higher tiller density can provide a denser stand, be more competitive with weeds, and sustain production in lower fertility and wetter soils. Diploids also tend to have a more prostrate growth (horizontal) type, which allows the stand to be more persistent in heavy grazing scenarios. Well-managed diploid leys will usually produce denser swards. Typically, diploids will have better ground cover rankings and are more suitable for wet soils or soils prone to poaching (AHDB, 2019).
- Tetraploid varieties have four sets of chromosomes (4n = 28) in each cell with larger cell sizes, wider leaves, larger seed size, greater content of soluble carbohydrates (sugar and starch), and less fibre content (Lemus, 2017). All other factors being equal, diploids have higher dry matter content (typically 18-26% DM) than tetraploids (15-20% DM), due to diploids having smaller cells and a lower cell wall to cell contents ratio. This means ruminants fed entirely on a

tetraploid sward will need to consume as much as one-third more fresh grass per day to achieve the same nutritional intake as from a purely diploid sward.

- Tetraploids have a slower recovery after grazing than diploids because they do not tiller as aggressively. They can also be susceptible to overgrazing because of higher palatability. Tetraploids have a more upright growth habit and are suited to drier growing conditions. As they do not tiller as vigorously as diploids, they are often good candidates for mixtures with clovers.

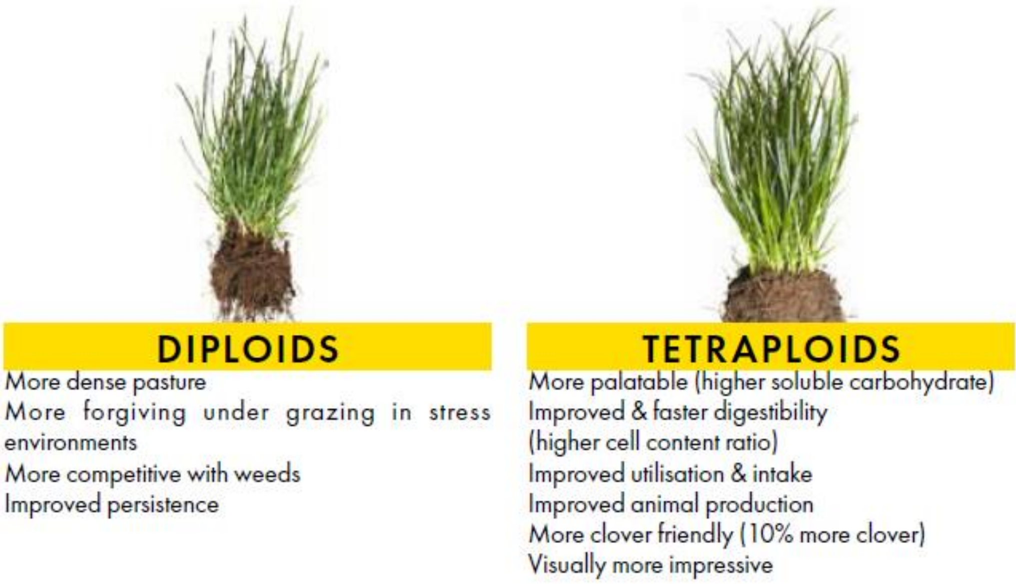


Figure 5. Diploid v tetraploid ryegrass. Source: Barenbrug, undated.

4 Biophysical requirement

- This section of the report details the requirements of each grass, clover or forage species and include a tabular summary of the biophysical requirements. The example table below is designed to facilitate understanding of the Tables that follow (Table 5).

Table 5. Notes on species requirement tables

Requirements	Min	Max	Notes
Climate			
Growing season (Days)	150	300	For annual crops this the number of days from planting/sowing to harvest. For perennial crops this is the number of days on which the crop is typically actively growing.
Air or ground frost	-3	0	An 'air frost' occurs when the temperature at 1.25 metres above the ground falls below 0°C, whereas 'ground frost' refers to a temperature below 0°C measured on a grass surface. The minimum temperature is the temperature furthest from 0°C and the maximum temperature is the temperature closest to 0° at which freezing damage occurs.
Other			Frequent or strong winds can be damaging to crops (e.g. breakage or wind scorch). Crops that have susceptibility to wind damage have been noted in the crop tables.
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [7]	24 [32]	This is the range of mean daily temperatures during the growing season which are optimum or [tolerable] for the crop, unless otherwise stated.
Rainfall (mm) Optimum & [tolerable] range	500 [300]	1000 [2500]	This is the annual rainfall, which is optimum or [tolerable] for the crop, unless otherwise stated.
Site			
Aspect			The compass direction in which the land/slope faces (e.g. south or west). The south side of a slope will receive more direct solar radiation than the north side (in the northern hemisphere). Daily and accumulated temperatures are higher on slopes with a southerly aspect than those facing in a northerly direction.
Altitude (m)			Altitude (above mean sea level), affects, for example, soil wetness and temperature. For the AT0, the lapse rate for temperature is 1.14 day °C/m (MAFF, 1988). For example, for two points which had the same National Grid easting and northing but a difference of 50 m in altitude the AT0 would be 57°C higher at the lower altitude.

			Rainfall and frost risk increase at higher altitudes.
Gradient (°)	0	7	The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. However, note that machinery use on some grazing grassland is likely to be minimal so gradient limitations may not be valid for those systems. The gradient limit for each crop is given based on the categorisation used in the ALC: grade 1 to 3a 7°; grade 3b 11°; grade 4 18° and grade 5 >18°.
Soil			
Soil pH Optimum & [tolerable] range	7.0 [5.0]	7.5 [8.3]	This is the soil pH, which is optimum or [tolerable] for the crop, unless otherwise stated.
Topsoil texture	S	C	This indicates the range of suitable soil textures for the crop, e.g. min S to max C means that the crop can be grown on S, LS, SL, SZL, ZL, MZCL, MCL, SCL, HZCL, HCL, SC, ZC & C. Abbreviations for topsoil texture are listed Table 6.
Depth (cm)	20-50	50-150	Soil depth is often the limiting factor affecting water availability, anchorage or nutrient availability. The minimum depth is the most crucial and is that required for the crop plant to access sufficient water and nutrients from the soil profile. Note that even where a soil has sufficient depth for crop growth other factors such as bulk density, soil structure, water table etc. can also impede root growth.
Stone content (%)	0	5 [10]	Stones can impede cultivation, harvesting and crop growth. In line with the ALC the limits are given for stones in the top 25 cm of the soil for two size classes, i.e. >2 cm and >6 cm. Limiting percentages are based on the volume of hard stones; stones >6 cm have a more detrimental effect than those >2 cm. Hence the limiting percentages (for ALC grades) are lower for larger stones. Where there is no specific information on crop requirements, the minimum and maximum stone limits are based on the limit values for the appropriate ALC grades for stones >2 cm [and >6 cm].
Drainage			This is related to available water capacity, soil wetness, moisture balance and field capacity.

Table 6. ALC soil texture class abbreviations

Abbreviation	Soil textural class	Notes
S	Sand	
LS	Loamy sand	
SL	Sandy loam	
SZL	Sandy silt loam	
ZL	Silt loam	
MZCL	Medium silty clay loam	<27% clay content
MCL	Medium clay loam	<27% clay content
SCL	Sandy clay loam	
HZCL	Heavy silty clay loam	≥27% clay content
HCL	Heavy clay loam	≥27% clay content
SC	Sandy Clay	
ZC	Silty Clay	
C	Clay	
P	Peat	
SP	Sandy peat	
LP	Loamy peat	
PL	Peaty loam	
PS	Peaty sand	
MZ	Marine light silts	

Table 7. Agricultural Land Classification of England and Wales: grades 1-5.

<table>
<tr><th>Grade</th><th>Quality</th><th>Limits</th><th>Cropping</th></tr>
<tr><td>1</td><td>Excellent</td><td>No or very minor limits to agricultural use.</td><td>• Wide range of crops including fruit, salad crops and winter harvested vegetables.
• High yields
• Low variation in yields</td></tr>
<tr><td>2</td><td>Very good</td><td>Minor limitations which might affect crop yield, cultivations or harvesting.</td><td>• Wide range of crops but may not be suitable for root crops or winter harvested vegetables.
• High yields
• More variation in yield.</td></tr>
<tr><td>3a</td><td>Good</td><td rowspan="2">Moderate limitations which affect the choice of crops, timing and type of cultivation, harvesting or yield.</td><td>• Wide range of crops including cereals, oilseed rape, potatoes and less demanding horticultural crops
• Moderate yields</td></tr>
<tr><td>3b</td><td>Moderate</td><td>• Cereals: moderate yields
• Grass: high yields
• Other crops: lower yields</td></tr>
<tr><td>4</td><td>Poor</td><td>Severe limitations which restrict the range of crops and/or yield.</td><td>• Mainly grass with occasional arable crops (cereals or forage crops)
• Variable yields</td></tr>
<tr><td>5</td><td>Very poor</td><td>Very severe limitations.</td><td>• Restricted to permanent pasture or rough grazing.</td></tr>
</table>

5 Grass species

5.1 Perennial ryegrass (Lolium perenne)

- Perennial ryegrass (PRG) is the most common sown grass grown in the UK due to its productivity and suitability to the climate and farming systems and it is the key component of most ley mixtures sown in the UK. Both diploid and tetraploid varieties exist; overall there are about 70 varieties of PRG on the Recommended Grass and Clover list, of which *c*.45% are diploids and *c*.55% tetraploids. A ryegrass tiller is made up of a basal stem, a leaf sheath and, at any one time, three growing leaves. As a fourth new leaf is produced the oldest leaf starts to die; subsequently when the fifth leaf is produced the second leaf dies. Grass should be grazed at the 2.5-3 new leaf stage.
- PRG will produce new tillers throughout the growing season with peak production occurring from late April to July. The time it takes for a tiller to produce three leaves will vary, depending on the plant, the local climate and the time of year. In mid-spring it may take 15 days for a tiller to produce three leaves, with a new leaf produced every five days thereafter. In colder periods, it may take up to 50 days for a tiller to reach the three-leaf stage, with a new leaf produced every 17 days (Barenbrug, undated).
- PRG produces persistently good yields of high-quality forage. It is a persistent, adaptable, long-lived species and can produce dry matter yields in excess of 15t/ha – especially in the first harvest year. Generally perennial ryegrasses have good winter hardiness, and they establish rapidly. However, due to the rather shallow rooting habit PRG has only limited drought tolerance (e.g. Bothe *et al.,* 2018). Their high sugar content makes them suitable for silage making.
- Early varieties have an erect growth and grow rapidly in the spring. They are suitable for early cutting and grazing mixtures; however, early varieties tend to have a lower mid-season production potential.
- Intermediate varieties have denser more prostrate growth than early PRG varieties as well as a longer growing season. The yield potential is high under both grazing and cutting management.
- Late varieties are persistent and form the main component of long-term leys designed for intensive cattle or sheep grazing. They have dense growth and as a result have a good resistance to treading. Yield potential is high and mid-season and end of season growth is good (SMG, 2015).

Requirement	**Min**	**Max**	**Notes**
Climate			
Growing period (Days)			Sow: April to September Perennial ryegrass plants will produce new tillers throughout the growing season with peak production occurring from late April to July. The time it takes for a tiller to produce three leaves will vary, depending on the plant, the local climate and the time of year. Flowering is initiated by a long photoperiod (Aamlid *et al.*, 2000). PRG does not have a dormant phase.

Air or ground frost	-6		PRG will withstand most frosts throughout the winter[4]. However, it may not survive very cold winters (Hannaway *et al*., 1999)
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	5 [0]	25	Minimum germination temperature is 7-8°C. Optimum growth is achieved between 20-25°C, with night temperature only slightly lower (IGER, undated). Or 18-20°C Mitchell, 1956. A vernalisation period of 9-12 weeks at <6°C for central European varieties or 12 or more weeks for Scandinavian varieties is required, although some Mediterranean varieties do not require vernalisation (Aamlid *et al*., 2000).
Rainfall (mm) Optimum & [tolerable] range	635 [450]		Minimum annual rainfall requirement is 450 to 635 mm (Thorogood, 2003 cited by Australian Government, 2003).
Site			
Aspect	~	~	
Altitude (m)	0	2000	It can grow in areas up to 2000 m (Popay, 2013).
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems.
Soil			
Soil pH. Optimum & [tolerable] range	6.0 [5.2]	7.5 [8.4]	If pH is not optimal (5.5-7.5), yield will be reduced (Hannaway *et al*., 1999).
Topsoil texture	S	SCL [C]	Most soil textures including heavy clay but prefers well-drained soils of medium to high fertility (Nadja, 2004).
Soil depth (cm)			Shallow root system. Roots can extract water to 80 cm deep (Garwood and Sinclair, 1979).
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Well drained soils. Low drought tolerance. It will tolerate long periods of flooding (15 to 25 days) when temperatures are below 27°C (Hannaway *et al*., 1999).

[4] https://www.cotswoldseeds.com/species/24/perennial-ryegrass

5.2 Italian ryegrass (Lolium multiflorum)

- Italian ryegrass has a shorter persistence than perennial ryegrass, generally lasting up to 3 years after establishment, depending on conditions (British Grassland Society, 2020). In some countries where the climate is more extreme it is also known as annual ryegrass, as persistence into a second year is unreliable. Italian ryegrass requires an ample supply of water and persistence can also be reduced by drought.
- Maturity or flowering date of each variety depends on its response to day length and vernalisation requirements (i.e. the requirement for a period of exposure to cold temperatures prior to flowering). Those varieties with a high cold requirement flower later because they take longer to accumulate their cold requirement over winter.
- Italian ryegrasses (IRG) have erect growth and mature 2-3 weeks earlier than the 'early perennials' (SMG, 2015). They tend to have a very open growth habit with fewer tillers than other grasses. They are therefore better suited to cutting than grazing and are typically used for silage, haylage and high-quality hay crops. However, the long growing season gives the opportunity for early spring grazing prior to cutting.
- IRG has high yield potential and establishment is fast providing ground cover within a few weeks of sowing. IRGs yields tend to be higher than PRG but they have poorer persistence (British Grassland Society, 2020).
- IRG has been the subject of plant breeding for many years, resulting in a wide range of commercially available varieties. There are currently 13 diploid and 11 tetraploid varieties of IRG on the Recommended Grass and Clover List for England and Wales for 2020/21 (British Grassland Society, 2020).

Requirement	**Min**	**Max**	**Notes**
Climate			
Growing period (Days)			Sow: late March to September There is no winter or cold weather requirement for IRG to flower and it will flower throughout the summer
Air or ground frost			Italian ryegrass will grow through the winter, but frost tolerance is improved if surplus growth is removed in the autumn[5].
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	3 [0]	25	Minimum germination temperature is 4-5°C (Barenbrug, undated). Optimum growth is achieved between 20-25°C (Hannaway *et al*., 1999). It is more tolerant of heat than PRG, but temperature stress will reduce summer production even if adequate water is available.
Rainfall (mm) Optimum & [tolerable] range	400	1500	
Site			
Aspect	~	~	
Altitude (m)	0	900 m	Normally grown at low altitudes but has been recorded up to 900 m.

[5] https://www.cotswoldseeds.com/species/27/italian-ryegrass

Gradient (°)			30% (>30% poor but possible). The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems
Soil			
Soil pH. optimum & [tolerable] range	6.0 [5.0]	7.0 [7.8]	Annual ryegrass grows best at a soil pH of 6.0 to 7.0 (Lemus, 2017).
Topsoil texture			Fertile well-drained soil. It will tolerate a range of soil types including clay or poorly drained but prefers loam or sandy loam soil (SARE, 2012). Loamy sand to sandy loam (
Soil depth (cm)	20 [<20]	>50	Extensive, shallow, fibrous root system.
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Well drained to poorly drained soils. It will tolerate long periods of flooding (15 to 20 days) when temperatures are below 27°C (Hannaway *et al*., 1999). More susceptible to soil moisture stress than PRG (Lucanus *et al*., 1960).

5.3 Hybrid ryegrass (Lolium multiflorum x)

- The hybrid ryegrass is a cross between Italian and perennial ryegrass; the dominant parent determines how the variety performs in the field. Most hybrid varieties are bred to combine the high yield of Italian varieties and the persistence of perennial varieties. In comparison, with Italian ryegrass the plants usually have more tillers and more leaf and give good ground cover which makes them suitable for cutting followed by grazing.
- The biophysical requirements of hybrid ryegrass depend on the dominant parent; requirements for PRG and IRG are detailed in the preceding Sections; as a result, a requirements table has not been compiled for hybrid ryegrass.

5.4 Festulolium

- Festulolium are any species cross between Italian or perennial ryegrass and any Fescue species. They are quick to establish and can be sown from March to September.
- The first Festulolium variety to gain entry onto the UK National Recommended Varieties List was, AberNiche in 2012. It is a tetraploid high yielding, winter hardy, and drought tolerant Italian ryegrass/Meadow Fescue species' combination produced by IBERS.
- Ryegrasses and Fescues offer a range of complementary traits that when combined provide varieties with high yields of nutritious fodder (from ryegrass) with resilience to a range of stresses both abiotic (drought, cold, flooding) and biotic (disease resistance). Festulolium varieties are increasingly gaining interest as sources of reliable, productive, and nutritive fodder for use in livestock agriculture and for their potential for ecosystem service provision (e.g. flood mitigation and carbon capture) (MacLeod *et al*. 2013). Importantly, Festulolium also has a higher tolerance to stresses such as drought or cold than perennial ryegrass (Ghesquière *et al*. 2010 cited by Humphreys *et al*., 2014).
- Festulolium varieties can grow on more variable soils than a pure ryegrass plant. The deeper root structure helps them establish under both dry conditions and on soils that suffer occasional waterlogging. They also have good frost tolerance.
- The biophysical requirements of Festulolium depend on the dominant parent; as a result, a requirements table has not been compiled.

5.5 *Timothy (Phleum pratense)*

- Timothy (*Phleum pratense*) is a tufted or single stemmed, short-lived, cool-season perennial grass that grows in clumps, reaching up to 150 cm in height. It is palatable to stock and particularly suitable for hay making and less suited to frequent heavy grazing.
- Timothy is a very winter hardy species which will persist well in wet conditions. It commences growth at lower temperatures than ryegrass so can be good for early grazing (SMG, 2015). It can be slow to establish, and yields are usually lower than PRG (AHDB, 2020). However, it typically outlasts ryegrasses in mixtures and despite its shallow root structure persists well on lighter soils in dry years[6].
- Timothy produces few tillers compared to PRG, however, the maximum number of leaves per tiller is 6-7, compared to only 3 for PRG. Due to the long lifespan of individual leaves, Timothy can accumulate a lot of biomass before senescence commences (Peeters, 2004 cited by Kasulyte and Praciak, 2015).
- There is considerable variation in flowering behaviour amongst different varieties of Timothy. In comparison with PRG, Timothy is late flowering, tending to head 6-10 weeks later than ryegrass. It has less production in winter but commences spring growth early (Hume and Lucas 1987) and provides a long period with high quality leafy pasture.
- When tested under 15-18-hour day length conditions Fiil *et al*. (2011) identified considerable variation in vernalisation response for Timothy varieties of different origins, collected from latitudes between 35° N and 70° N. Vernalisation accelerated flowering and development of Timothy in all tested cultivars and accessions (Seppänen *et al.,* 2010; Fiil *et al*., 2011; Jokela *et al*., 2014), although Jokela *et al*. (2014) noted that some cultivars were able to flower without vernalisation when the photoperiod was 16 hours.
- There are nine varieties of Timothy on the recommended variety list for 2020-21.

Requirement	**Min**	**Max**	**Notes**
Climate			
Growing period (Days)			Timothy does not require vernalisation, but flowering is triggered by long days; however, vernalisation may accelerate flowering and development in northern accessions (Jokela *et al*., 2015). Timothy can be sown in autumn and spring when soil temperatures are above 10°C (Charlton *et al*. 1986). Harvest in spring during late boot (seed head enclosed in the sheath of the flag leaf) to early flowering stage (Lacefield *et al*, 2002).
Air or ground frost			Very winter-hardy, exhibiting tolerance of both cold temperature and ice encasement.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range			Timothy can also reproduce vegetatively through tillering (Esser, 1993 cited by Kasulyte and Praciak, 2015). It does not tolerate prolonged high temperatures. Warm average temperature (>10°C).

[6] https://www.cotswoldseeds.com/species/67/timothy

Rainfall (mm) Optimum & [tolerable] range	450		Annual rainfall of at least 450 mm (Ogle *et al*, 2011).
Site			
Aspect	~	~	
Altitude (m)	0	2500	It grows over a wide range of altitudes.
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems
Soil			
Soil pH. optimum & [tolerable] range	5.5	7.0	According to Ogle *et al*. (2011), Timothy is adapted to soils with a pH of 5.5 to 7.0.
Topsoil texture			Medium to heavy. Clays to loams.
Soil depth (cm)			Shallow, compact and fibrous root system.
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Tolerant of winter flooding but not during the growing season (Mudd and Mair, 1961 cited by Charlton and Stewart, 2000). Sites where water stands for extended periods should be avoided, although it can tolerate somewhat poorly drained soils (Ogle *et al*., 2011). It does not tolerate drought and has shallower roots than PRG (Ogle *et al*., 2011).

6.1 Cocksfoot (Dactylis glomerata)

- Cocksfoot is a tussocky perennial grass which persists well under appropriate grazing management. Heavy grazing in autumn, winter or early spring when growth is slow will damage the grass and it is not tolerant of heavy trampling. The plants may be severely damaged by overgrazing especially in the seedling year (Bush *et al*., 2006). It grows relatively slowly following establishment but in the second and subsequent years it grows well.
- Cocksfoot starts growing early in the spring and regrowth after cutting consists mostly of leafy palatable shoots[7]. Excellent summer growth results in high summer production. Early types are mainly used for conservation. Late types are excellent for grazing.
- In comparison with ryegrass, Cocksfoot establishes more slowly and has lower nutritional value, but has much better summer growth and survival (Lolicato and Rumball, 1994.). Newer smooth-leaved varieties have been developed which are more palatable than the hairier traditional varieties[8].
- Due to its extensive rooting system, Cocksfoot has better persistence than perennial ryegrass on sites where the soils are prone to dry out quickly and where soil fertility is sub-optimal. (Lolicato and Rumball, 1994).
- The diversity of environments in which Cocksfoot developed has given rise to two distinct subspecies. The first is the temperate type (*Dactylis glomerata* ssp. *glomerata*), which originated in cooler northern regions of Europe and Asia. The second is the Mediterranean type (*Dactylis glomerata* ssp. *hispanica*), which originated in the summer-dry areas of southern Europe and North Africa.
- Spanish Cocksfoot species become dormant at the end of spring when temperatures rise and remain dormant until sufficient rainfall is received in autumn and temperatures decline. This sub-species is very drought hardy. Temperate Cocksfoot species maintain active growth throughout the year and have poorer drought tolerance. There are also intermediate types that show facultative dormancy, i.e. they will cease growing if soil moisture is limiting.

Requirement	**Min**	**Max**	**Notes**
Climate			
Growing period (Days)			Sown between March and early May or in the autumn between August and September. Before flower shoot initiation can take place, plants must be subjected to a period of cold and then receive a photoperiod of at least 12 hours. Most growth occurs in April and May with a second peak in July.
Air or ground frost			It can withstand winter temperature as low as -42°C (Bush *et al*., 2006). Late spring frost can injure the developing flowers and florets can be aborted (Beddows, 1959). Frost can cause the leaves to die back from the tip.

[7] https://www.dlf.co.uk/forage-grass-seed/species/dlf-uk/forage-grass-species/cocksfoot-prod368

[8] https://www.britishgrassland.com/news/preference-new-cocksfoot

Other	~	~	Similarly, to frost, strong, cold or salt-laden winds can cause the grass to die back from the tip.
Mean daily air temperature (°C). Optimum & [tolerable] range	7 [4]	22 [25]	Leaves are produced throughout the year whenever the temperature is ≥5°C (Beddows, 1959). Optimal growth is achieved when daytime temperatures are between 18°C and 22°C. (Baker and Jung 1968). Data from New Zealand report that the grass is found in areas where annual mean temperature ranges from *c*.7-16°C (lowest mean monthly temperature -4°C, highest mean monthly temperature 25°C (Campbell *et al*., 1999).
Rainfall (mm) Optimum & [tolerable] range	400		Depends on variety. Data from New Zealand report that the grass is found in areas where annual mean rainfall ranges from *c*.400 to >4000 mm (Campbell *et al*., 1999).
Site			
Aspect	~	~	
Altitude (m)		2400	It is uncommon in the UK above 540 m but found at higher altitudes elsewhere (Beddows, 1959).
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems.
Soil			
Soil pH optimum & [tolerable] range	6.0 [5.0]	7.0 [8.5]	Moderate to high fertility soils (Beddows, 1959). It can tolerate pH as high as 8.5.
Topsoil texture			Clay to loams (Bush *et al*., 2006). Light sand to wet clays[9]
Soil depth (cm)			Shallow to deep soils (Bush *et al*., 2006).
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			It has a comprehensive root structure travelling to depth and therefore thrives on light, free-draining soil. It is also suitable for soils prone to flooding but does not tolerate very wet conditions.

[9] https://www.cotswoldseeds.com/articles/20/cocksfoot-the-black-sheep-of-the-grass-family

6.2 *Bent (Agrostis sp.)*

- Common Bent (*Agrostis capillaris*) is a native rhizomatous, perennial grass, common and widely seen on acid grassland, damp soils, meadows, pasture and rough ground (Bond *et al*, 2007). It grows on nutrient poor meadows, heathland and forest gaps and is characteristic of upland pasture in short turf (Weber, 2003 cited by Bond *et al.,* 2007).
- Common Bent is a delicately flowered grass that is often included in agri-environmental seed mixes. It is a creeping grass and, although of little agricultural value, is very common in old grasslands. It is adaptable to most soils and is drought tolerant[10].
- The shoots wither in late summer making it of limited grazing value in many pastures. However, it is an important staple in upland sheep pasture in regions of high rainfall.

Requirement	Min	Max	Notes
Climate			
Growing period (Days)			Common bent flowers from June to August (Clapham *et al*., 1987).
Air or ground frost			Resistant to summer heat and winter cold (Maczey, 2016).
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range			Data from New Zealand report that the grass is found in areas where annual mean temperature ranges from c.7-16°C (Lowest mean monthly temperature -4°C, highest mean monthly temperature 25°C (Campbell *et al*., 1999).
Rainfall (mm) Optimum & [tolerable] range	400 [300]	4000	Data from New Zealand report that the grass is found in areas where annual mean rainfall ranges from c.400 to >4000 mm (Campbell *et al*., 1999).
Site			
Aspect	~	~	
Altitude (m)	0		In the UK it is found from sea level to mountain tops (>1200 m) and at >2000 m elsewhere[11]
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems.
Soil			
Soil pH. optimum & [tolerable] range	6.5 [4.9]	7.2 [7.5][12]	It is not suited to calcareous or alkaline soils.
Topsoil texture			Fine to medium textured soil (Bond *et al*., 2007a).
Soil depth (cm)	30		

[10] https://www.cotswoldseeds.com/articles/475/grasses-for-farmers

[11] http://issg.org/database/species/ecology.asp?si=1365&fr=1&sts=&lang=EN

[12] https://plants.usda.gov/java/charProfile?symbol=AGCA5

Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass for conservation. Common bent is only rarely included in swards that are cut for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Optimal growth occurs on freely drained or fairly dry soils, but *A. capillaris* can also be abundant on poorly drained and damp soils when inhabiting wetlands (Rapson and Wilson, 1992).

6.3 Fescue (Festuca sp.)

- Species within the genera Festuca have a higher level of general stress tolerance compared with perennial ryegrass (Rudi *et al*., 2011). There are two types of fescues: fine and broad-leaved. The fine fescues include Sheep, Hard, Chewing's and Red Fescue; the broad-leaf types include Tall and Meadow Fescues. Recently the broad-leaved, agronomically important, fescues were given their own genus *Schedonorus* which separates them from the finer leaved fescues.
- Meadow Fescue (*Schedonorus pratensis (Festuca pratensis)*) is a long duration grass that is often sown with Timothy to provide hay or grazing. For longer term leys it is an alternative to perennial ryegrass, especially in upland areas. It will grow on nearly all soils ranging from light, brashy types to heavy clays. It has the same growth habit as perennial ryegrass and, although more persistent and drought tolerant, is slower to establish[13].
- Meadow Fescue is a very persistent grass. It does not require high temperatures for active growth and is very winter hardy. It performs well in wet soils but can be grown successfully on a wide range of soils. Early spring growth yield is good, and regrowth consists mainly of leafy shoots which are ideal forage[14]. It has good palatability, and the wide leaves produce good hay.
- Tall Fescue (*Schedonorus arundinacea (Festuca arundinacea*)) is found throughout the UK, it has similar features to Meadow Fescue, however it is taller, and coarser, with a rough upper leaf and margins. The well-developed root system means it is tolerant of drought, damp and frost.[15].

Requirement	**Min**	**Max**	**Notes**
Climate			
Growing period (Days)			Tall fescue has a greater need to be exposed to low winter temperatures (vernalisation) to induce flowering than does perennial ryegrass. A spring planting of tall fescue will not flower (Anderson *et al.,* 2014).
Air or ground frost			Meadow Fescue is very winter hardy. Tall Fescue has very good frost tolerance.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	4	35	Tall Fescue will produce top growth when soils are ≥4°C. Tall Fescue can maintain growth up to ambient temperatures of 35°C.
Rainfall (mm) Optimum & [tolerable] range	500 [375]	2000	A minimum precipitation range is typically 375 to 450 mm, although in areas of high evapotranspiration, up to 900 mm is required for good growth (Watling, 2016).
Site			
Aspect	~	~	
Altitude (m)	0	1524	Sea level to 1524 metres (Cowan, 1956).
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where

[13] https://www.cotswoldseeds.com/articles/475/grasses-for-farmers

[14] https://www.dlf.co.uk/forage-grass-seed/species/dlf-uk/forage-grass-species/meadow-Fescue-prod341

[15] https://www.cotswoldseeds.com/species/65/Tall-Fescue

			machinery use is likely to be minimal; gradient limitations may not be valid for those systems.
Soil			
Soil pH. optimum & [tolerable] range	5.5 [4.7]	7.0 [9.5]	it can tolerate a wide range of soil pH, from strongly acidic (pH 4.7) to alkaline (pH 9.5) (Watling, 2016).
Topsoil texture			Medium to heavy soils.
Soil depth (cm)		>50	Tall fescue has a dense fibrous root system. capable of extracting water from over 100 cm into the soil.
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Tall Fescue can grow under conditions ranging from excessively drained to poorly drained and can tolerate long periods of flooding (24 to 35 days) when temperatures are below 27°C. (Watling, 2016).

6.4 Yorkshire Fog (Holcus lanatus)

- Yorkshire Fog is a tufted, fibrous rooted, perennial grass native on rough grassland. It is well adapted to growing in wet conditions but can survive a moderate drought, although growth is markedly reduced under dry conditions (Watt, 1978)
- It cannot tolerate heavy grazing (it has a small number of large tillers) or trampling (the growing point is above ground), however it is less palatable than PRG.

Requirement	Min	Max	Notes
Climate			
Growing period (Days)			In general, plants require vernalisation in order to flower, with a minimum exposure of 25-28 days and a temperature of less than 5°C (Thompson and Turkington, 1988).
Air or ground frost			Severe frost has been found to kill Yorkshire Fog under certain conditions (Thompson & Turkington, 1988)
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	12 [5]	29	Leafy shoots are continually being renewed when the temperature is ≥5°C (Beddows, 1961). Grows at temperatures between 12-29°C.
Rainfall (mm) Optimum & [tolerable] range		800	
Site			
Aspect	~	~	
Altitude (m)		1500	In the UK it is found up to 600 m (Beddows, 1961).
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems.
Soil			
Soil pH optimum & [tolerable] range	5.0	7.5	It tolerates a wide range of pH values, but optimum is 5.0-7.5 (Thompson and Turkington, 1988).
Topsoil texture			Wide range of soil textures (Jacques, 1962).
Soil depth (cm)			Tendency to develop surface roots may make it vulnerable to drying out (Beddows, 1961).
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Not drought tolerant Grows well under very wet conditions, although optimal growth occurs under moist conditions, and it

			can survive moderate periods of drought, although the growth rate will be reduced (Watt 1978).

7 Other species

7.1 White Clover (Trifolium repens)

- White Clover is a low growing short-lived perennial and will persist for 3 to 5 years under good growing conditions. It spreads by stolons and forms shallow roots at nodes. It is often grown with a companion grass, typically ryegrass, with the type of ryegrass being dependent upon the primary use of the sward.
- White Clover is a Mediterranean species that thrives in warm, moist soil conditions and grows exceptionally well in moist maritime-influenced Mediterranean climates. (Lacefield and Ball, 2000). It has a high nutritional value (particularly protein) and good palatability resulting in good animal performance and can be used for grazing and cutting (British Grassland Society, 2020). Clover can survive dry conditions as the stolon's act as a reserve of resources during times of stress (Humphreys and Lawless, 2006). However, clover is not tolerant of longer-term drought.
- Rhizobium bacteria, which exist symbiotically within 'nodules' on clover roots, convert nitrogen from the air into a form that can be utilised by the plant (nitrogen fixation). The nitrogen becomes available for companion grasses and/or subsequent crops as it is released following plant decay. It has been estimated that the utilisable nitrogen generated through the fixation process is equivalent to 100-150 kg N/ha in a well-balanced and stable grass and clover sward (BSH and IBERS, undated). The Rhizobia bacteria perform best in free draining soils because the pore spaces in the soil remain relatively water-free.
- There are 15 varieties of White Clover on the Recommended List for 2020/21.

Requirement	Min	Max	Notes
Climate			
Growing period (Days)			Sow April to August to ensure that seedlings can begin producing stolons before winter. It is often sown with grass or into an existing grass sward. White Clover produces flowers rather intermittently at any time during the summer from May through to September.
Air or ground frost			Clover leaves are prone to frost damage, but it is winter hardy.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range			The growth of clover starts when soil temperatures reach around 9°C. From early November to mid-April soil temperatures are typically too low both for clover growth and for N fixation. The clover goes into decline and eventual dormancy over the winter period. (Humphreys and Lawless, 2006
Rainfall (mm) Optimum & [tolerable] range	775 [700]	1300 [2000]	White clover grows best where annual rainfall is between 900–1300 mm and conditions are cool. and moist (Smith and Valenzuela, 2002).
Site			
Aspect	~	~	
Altitude (m)		2100	It grows at a variety of altitudes (Smith and Valenzuela, 2002).

Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems.
Soil			
Soil pH. optimum & [tolerable] range	6.0 [5.5]	6.5 [7.0]	Optimum pH is 6.0-6.5 (Humphreys and Lawless, 2006).
Topsoil texture			Free draining loam soils; also clay and silt soils and sandy soils with a high-water table (Ogle and St John, 2008).
Soil depth (cm)			It is a relatively shallow rooted species making it intolerant of droughty soils (Hall, 1993).
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass/clover for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Soils that maintain a relatively high soil moisture status during the summer. However, it does not tolerate waterlogging and does not do well on wet soils (Humphreys and Lawless, 2006).

7.2 Red Clover (Trifolium pratense)

- Red Clover is a short-lived perennial herbage legume that typically persists for 2-4 years. In contrast to White Clover, it has an upright growth form and a strong deep tap root from which finer roots grow. The crown, located at the base of the stem, acts as a store of nutrients (BSH, IBERS undated). It is adapted to areas with moderate summer temperatures and adequate moisture throughout the growing season.
- Red Clover can fix atmospheric nitrogen through symbiosis with the bacteria *Rhizobium leguminosarum biovar trifolii,* which allows it to attain high forage yields even without N fertilization.
- Red Clover is, by nature, a diploid species (2n = 2x = 14), but tetraploid (2n = 4x = 28) varieties also exist in commercial production. Tetraploid Red Clover generally attains up to 20% higher forage yields and is generally more tolerant to biotic and abiotic stresses compared to diploid Red Clover (Vleugels *et al*., 2019).
- Red Clover is mainly used for silage production and has a high protein content (up to 19% depending on the percentage in the sward); it produces a high yield even without N fertiliser. Early Red Clovers can produce two main cuts and a small autumn cut (British Grassland Society, 2020).
- There are 15 Red Clover varieties on the recommended list for 2020/21.

Requirement	**Min**	**Max**	**Notes**
Climate			
Growing period (Days)			April-late July is the optimum sowing period on most UK farms. Early varieties flower towards the end of May and late varieties 10-14 days later. Early flowering varieties start growth earlier in the spring, giving approximately 40% of annual yield for the first cut with progressively lighter yields in subsequent cuts (Conaghan and Clavin, 2017).
Air or ground frost	-6		The plant overwinters as crowns. This structure should be tolerant of all but the most severe frosts[16]
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range			
Rainfall (mm) Optimum & [tolerable] range	800 [700]		
Site			
Aspect	~	~	
Altitude (m)			
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. It is likely that land with a significant slope (>15°) will only

[16] https://www.cotswoldseeds.com/species/49/red-clover

			be used for grazing (rather than cutting) where machinery use is likely to be minimal; gradient limitations may not be valid for those systems.
Soil			
Soil pH optimum & [tolerable] range	6.0 [5.0]	6.5	Soil pH should be 6 or above (BSH and IBERS, undated) but it will grow on moderately acid soils (St John and Ogle, 2008).)
Topsoil texture			Medium and fine textured soils are better than sandy or gravelly soils (St John and Ogle, 2008). It does not persist well on very sandy soils (Undersander *et al*. 1990).
Soil depth (cm)			Red Clover is relatively drought tolerant due to its deep tap root. It offers superior production to White Clover in dry summers (Conaghan and Clavin, 2017).
Stone content (%) (silage/hay)	0	35 [20]	Stony soils may influence the field operations that are used to establish new swards, renovate existing ones or cut grass/clover for conservation.
(grazed only)		<70 {<35}	Stony soils are unlikely to cause significant barriers to livestock grazing. However, where soils are extremely stony (>70%) sward improvements may be difficult.
Drainage			Well drained soils are best, but it will also grow on soil that is not well drained (St John and Ogle, 2008).

7.3 Chicory

- Chicory (*Cichorium intybus* var. *sativum* (root chicory) or var. *foliosum* (cooked/salad chicory)) is grown for its swollen taproot. Chicory root can be dried and used in pet foods, roasted and used in drink flavouring or processed to extract inulin (used as a sweetener, a source of soluble fibre or converted to ethanol for use as a biofuel).
- Chicory can also be used as a forage crop (broad-leaved varieties) for livestock; it can help control parasitic worms in ruminant livestock (Rosenfeld and Rayns, undated).
- Chicory has a long taproot which can penetrate to depth and there is some evidence of improved drainage and soil physical properties where chicory has been grown[17]. Chicory typically persists for 3-4 years but can last for up to 10 years when not heavily grazed. Chicory is especially sensitive to any residue in the soil of a hormone herbicide. Such herbicides, including clopyralid, should be avoided in the previous crop.

Requirements	**Min**	**Max**	**Notes**
Climate			
Growing season (Days)	180	210	Sow: Mid-April to mid-August (later sowing is a part of a mixed sward for grazing). Harvest: Late September to October. Fodder crops: Persistency 2-5 years (AHDB, 2013). Chicory is dormant during winter.
Air or ground frost			Tolerates light frosts, however exposed sites with a history of light spring or early autumn frosts are best avoided. A cold period is required to induce flowering.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	13 [7]	24 [30]	The optimum temperature for chicory growth lies between 13°C and 24°C (Red Tractor Assurance, 2016). Growth ceases if temperatures are <7°C or >30°C. Soil temperature should reach ≥10°C before planting in the spring (AHDB, 2013).
Rainfall (mm) Optimum & [tolerable] range	1500 [300][18]	2500 [4000]	Requires well distributed rainfall (DAFF (2013b).
Site			
Aspect			Warm south facing fields are preferred. North facing fields should be avoided.
Altitude (m)			Land at high altitude will be unsuited due to factors such as soil wetness and temperature (i.e. AT0 <1100°C).
Gradient (°)	0	7	The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. 7° is the ALC limit for grade 1 to 3a land.
Soil			
Soil pH Optimum & [tolerable] range	6.0 [4.8]	6.8 [8.3]	Chicory will tolerate acid soil conditions (pH 5.0 to 6.8), although growth is better if pH lies between 6.0 and 6.8. Fields with a wide range of pH values can produce satisfactory crops if the cation exchange capacity (CEC) of

[17] https://www.cotswoldseeds.com/species/5/chicory

[18] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=694

			the soil is above 10meq/g soil (Red Tractor Assurance, 2016j).
Topsoil texture	S	SCL	Most soil types. Medium to light soils are best. Clay soils may adhere to the roots and need removing before storage.
Depth (cm)	20-50	50-150	Deep tap root.
Stone content (%)	0	5 [10]	
Drainage			Well drained

7.4 Lucerne

- Lucerne (*Medicago sativa*), also known as alfalfa, is a widely grown leguminous forage crop globally. However, it remains a minority crop in Great Britain despite its high yields, protein content and zero nitrogen fertiliser requirement (Evans and McConnell 2015). Lucerne can be baled or clamped but is difficult to ensile under UK conditions (high humidity coupled with low sugar content). The crop can also be rotationally grazed, but grazing can reduce crop persistency.
- Lucerne is not suitable for heavy or waterlogged soils where conditions are likely to rot the deep taproot and it is not suited to areas with high rainfall (AHDB, 2016). However, it is a drought tolerant species which can grow on thin, gravelly soils.
- It is slow to establish (putting energy into root development before leaf and stem production) but under appropriate conditions can last 4-5 years (AHDB, 2016). Varieties vary in their winter hardiness and dormancy ratings are applied to the plants; higher dormancy ratings indicate greater winter activity. A dormancy rating of 4-5 is considered optimal for UK conditions. Flemish or Northern varieties of Lucerne are most suited to UK conditions being more tolerant of cold conditions than Provence (Southern) varieties.
- Lucerne is auto-toxic, meaning that its seeds will not grow in a field of established Lucerne (a gap of 5-6 years is required between crops) (Undersander *et al*., 2011).

Requirements	Min	Max	Notes
Climate			
Growing season (Days)			Perennial with a period of winter dormancy. Sow: late April to mid-August (if soil moisture is not limiting). Cut: mid-May onwards (depending on location); 4-5 cuts are possible typically at 5-week intervals. Note: only 1-2 cuts may be harvested in the first year.
Air or ground frost			Foliage of lucerne dies off over winter but resumes growth from its crown in the spring[19].
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	21 [5]	27 [45]	Will not grow when the soil temperature is <8°C (AHDB, 2016).
Rainfall (mm) Optimum & [tolerable] range	600 [350]	1200 [2700][20]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as soil wetness and temperature (i.e. AT0 <1000°C).
Gradient (°)	0	11	Slightly sloping land is OK, providing that farming operations are still practicable.

[19] https://www.cotswoldseeds.com/species/34/lucerne

[20] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=1428

			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. 7° is the ALC limit for grade 1 to 3a land and for 3b it is 11°.
Soil			
Soil pH Optimum & [tolerable] range	6	8.5	Lucerne has a high requirement for calcium (McConnell and Genever 2015).
Topsoil texture	S	ZL	Suitable for a wide range of free draining soils; not suitable for heavy clay soils.
Depth (cm)	50	>150	Very deep taproot (> 6m) (Undersander *et al*., 2011). There have been some reports of lucerne roots going down as far as 15 m in search of water (AHDB, 2016).
Stone content (%)	0	20 [35]	
Drainage			Well drained soil.

7.5 Trefoils (common Birdsfoot)

- Birdsfoot Trefoil (*Lotus corniculatus*) is a perennial legume that provides good quality forage on soils considered unsuitable for other forage legumes (Collins *et al*., 2006). Currently, trefoil is not commonly grown in the UK, which may reflect difficulties with establishment. However, it has been found to be palatable to stock, non-bloating and to reduce internal parasites in sheep.
- Birdsfoot Trefoil can be successfully ensiled, with evidence that the tannin concentration in the forage reduces protein degradation during the ensiling process (Abberton, 2010). Trefoil may be grown as a pure stand or in a mixture with grass although the grass species should be carefully selected to ensure they do not out compete the trefoil.

Requirement	**Min**	**Max**	**Notes**
Climate			
Growing season (Days)			Sow: spring when soil temperature at 10 cm is *c*.10°C. Graze: two to three times annually (beginning at first flowering). The last grazing should end in late summer to allow plants to build reserves for overwintering. Harvest: for hay or silage at early flowering for optimum yield and quality. A day length of about 16 hours is required to initiate flowering (Undersander *et al*. 1993).
Air or ground frost	-7	1	Frost tolerance varies according to variety, but it is generally winter hardy.
Other			Requires a sunny site as it is not shade tolerant (Döring and Howlett, 2013).
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [3]	25 [30][21]	
Rainfall (mm) Optimum & [tolerable] range	600 [1000]	1000 [1900]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as soil wetness and temperature (i.e. AT0 <800°C).
Gradient (°)	0	18	The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. 7° is the ALC limit for grade 1 to 3a land, for 3b it is 11° and for 4 it is 18°.
Soil			
Soil pH Optimum & [tolerable] range	6 [4.5]	7 [8.2]	
Topsoil texture	S	C	Wide range of soil types
Soil depth (cm)	20-50	50-150	

[21] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=7410

Stone content (%)	0	35 [50]	
Drainage			High drought tolerance and tolerant to limited waterlogging.

7.6 Sainfoin

- Sainfoin (*Onobrychis viciifolia*) is a perennial forage legume which can be cut for hay or silage or grazed (sometimes as part of a grass/legume mix). It is highly palatable to livestock, does not cause bloat and is reported to help with parasitic worm control. Sainfoin is often grown with grass species such as Meadow Fescue or Cocksfoot and typically persists for 4 years. However, the seed rate of the grass must be kept low to avoid out competing the Sainfoin.
- Sainfoin grows well in areas that are dry and drained but grows very poorly on waterlogged land. In the UK, Sainfoin is typically associated with calcareous chalky or limestone soils.

Requirements	Min	Max	Notes
Climate			
Growing season (Days)			Sow: April to July. Harvest: During the flowering period (May to October); the first cut is traditionally taken at the bud to mid-flowering stage (Carbonero, 2011). One to three cuts can be taken per year. The recommended interval between cuts is about 6 weeks.
Air or ground frost			There are very few studies into sainfoin frost tolerance; it is not believed to be especially sensitive to low temperatures (Ortiz and Smith, 2011).
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	18 [4]	27 [34][22]	Sainfoin should be drilled between 10-20°C and not below 5°C (Ortiz and Smith, 2011).
Rainfall (mm) Optimum & [tolerable] range	330 [250]	800 [1100]	In the absence of irrigation, annual rainfall should be at least of 330 mm (Ortiz and Smith, 2011).
Site			
Aspect	~	~	
Altitude (m)			Optimum is 600 m above sea level, although it can grow between 100 and 2500 m (Ortiz and Smith, 2011). Land at high altitude will be unsuited due to factors such as soil wetness and temperature (i.e. AT0 <1000°C).
Gradient (°)	0	11	The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. 7° is the ALC limit for grade 1 to 3a land and for 3b it is 11°.
Soil			
Soil pH Optimum & [tolerable] range	6.6	8.0	Sainfoin establishes well in alkaline and neutral soils with pH >6 (Döring and Howlett, 2013). Poor establishment is obtained on clay soil at pH 6 (Ortiz and Smith, 2011).
Topsoil texture	S	SCL	Chalk, limestone, medium loam and sandy soil (Hill, 2017).
Depth (cm)	20-50	50-150	

[22] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=8079

Stone content (%)	0	20 [35]	It will thrive on very stony soils such as are found in the Cotswolds[23]
Drainage			Well drained; it does poorly on waterlogged soils.

[23] https://www.cotswoldseeds.com/articles/132/growing-sainfoin

7.7 Plantain

- Narrow-leaf Plantain or Ribgrass (*Plantago lanceolota*) is a perennial herb with a broad distribution in the native grasslands of the temperate world (Laws and Genever, 2013). The first ever plantain cultivar, 'Grasslands Lancelot' to be bred for pasture use originated in New Zealand in 1993 (Rumball *et al*., 1997). Initially there were only two varieties of plantain commercially available: Grassland Lancelot and Ceres Tonic, the latter was the most used variety. However, other cultivars are now available, e.g. Tuatara[24], Agritonic, Boston, Captain, Ecotain and Oracle. The crop is now used as a stand-alone crop and as part of a sward for ruminants across the world.
- Narrow-leaf Plantain is a deep-rooted, smooth-leaved perennial herb with a rosette growth form. It has dense upright foliage with leaves typically reaching 25 cm long and flowering stems 60-90 cm long. Under optimum growing conditions plantain can yield up to 20 t DM/ha, although 8–9 tonnes DM/ha may be more likely in the UK.
- A study in New Zealand, suggested that plantain can persist for a minimum of three years (Moorehead and Piggot, 2009). However, plantain may be out competed by other legume or grass species in a mixed sward. The persistency of plantain in a mixed sward will be increased by selecting uncompetitive companion species, a dry climate and generally low soil fertility. In addition, plantain requires short, intensive periods of grazing with sufficient rest/recovery periods in between. Withholding grazing during the winter increases yield by >50% the following spring and summer.
- Plantain is highly palatable, and many studies have shown that in a mixed pasture animals will selectively graze it (Stewart, 1996). Plantain has also been identified as having anthelmintic properties which helps with the control of parasitic worms.
- For successful establishment plantain should not be grazed until the plant has six fully grown leaves and the root system is fully developed (Nickerson, 2017).

Requirement	Min	Max	Notes
Climate			
Growing period (Days)			The plant is winter-active, but the growth rate is low. The main periods of growth occur in spring and autumn. Late spring sowing is recommended in the UK, as growth is limited at low soil temperatures. Sowing in the autumn as part of mixed sward is likely to lead to poor establishment of plantain, as other sward species are likely to outcompete it and dominate the sward. It requires long days to induce flowering (Cavers *et al*., 1980).
Air or ground frost			Moderately tolerant to frost. Considerable summer heat tolerance (Stewart, 1996).
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range			Sow into a warm soil, 10-12°C (Nickerson, 2017).

[24] https://www.lgseeds.co.uk/products/forage-crops/tuatara-forage-plantain/

Rainfall (mm) Optimum & [tolerable] range			It requires an annual rainfall above 500 mm.
Site			
Aspect	~	~	
Altitude (m)	0	800	It is recorded up to 800 m (Bond *et al*., 2007c).
Gradient (°)			The safe and efficient use of machinery on sloping land depends very much on the type and design of the machine and on the nature of the slope being farmed. 7° is the ALC limit for grade 1 to 3a land and for 3b it is 11°.
Soil			
Soil pH. optimum & [tolerable] range	4.2	7.8	Optimum is pH 5.8 (Troelstra and Brouwer, 1992, cited by Stewart, 1996).
Topsoil texture			Plantain is adapted to a wide range of soils but does not grow well in deep sands or waterlogged soils.
Soil depth (cm)			
Stone content (%)			
Drainage			It is relatively drought resistant and able to grow on dry sites (Bond *et al.,* 2007c).

8 Rooting

- Plant roots are crucial for water and nutrient uptake which control dry matter yield and quality. Root growth is strongly seasonal (Matthew *et al*., 2016) but mediated by other factors, such as soil moisture characteristics (drought or waterlogging) or nutrient availability.
- Grass roots consist of both seminal and adventitious roots. Seminal (seed) roots are short lived and do not live beyond the first season. Adventitious roots are produced from the basal nodes of tillers. Hairs on the roots increase the plant's capacity to absorb nutrients and water.
- Rooting depth, root morphology and root architecture all influence the ability of plants to access water and nutrients (Nichols *et al*., 2016). A higher proportions of root mass in deeper soil layers, or a greater maximum rooting depth, is likely to increase access to subsoil water (Grieu *et al*., 2001) and increase interception of mobile nutrients such as nitrate, (Dunbabin *et al*., 2003).
- Forage crops grown in highly fertilised monocultures have maximum above ground production and forage quality as the main breeding objectives. As a result, many of the current high yielding varieties of forage species are relatively shallow rooting which will compromise both their long-term persistency and yield potential following onset of drought conditions (Humphreys *et al*. 2014).

8.1 Root depth

- Plant rooting depth affects ecosystem resilience to environmental stress such as drought (Fan *et al*., 2017). However, rooting depth is not necessarily a fixed characteristic of individual plant species or cultivars, and root growth will vary depending on soil conditions. For example, root proliferation in nutrient-rich soil micro-sites is a well-documented phenomenon (Hodge 2004). Soil drying can also cause root proliferation at lower depths where moisture remains plentiful (Skinner *et al*., 1998; Skinner, 2008).
- Root systems of temperate grassland species can grow to great depths. In a global analysis, Canadell *et al*. (1996) found a maximum rooting depth of 2.6 ± 0.2 m for temperate grasslands. In comparison, Schenk and Jackson (2002) reported a mean maximum depth of 1.3 m for perennial grasses, although there was large variation around the mean value (Figure 6). However, most roots are found at much shallower depths where concentrations of nitrogen, phosphorus and potassium tend to be highest (Jobbágy and Jackson, 2001). Oxygen deficiencies are also least likely in shallow soil layers. In general, temperate grasslands allocate about 40% of their roots to the top 10 cm of the soil profile, and on average 83% occur in the top 30 cm (Jackson *et al*., 1996), Figure 7.

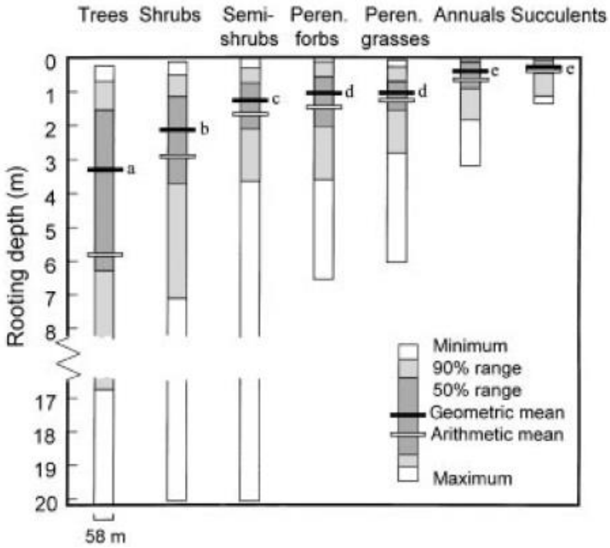


Figure 6. Maximum rooting depth of plant growth forms. (Source: Schenk and Jackson, 2002).

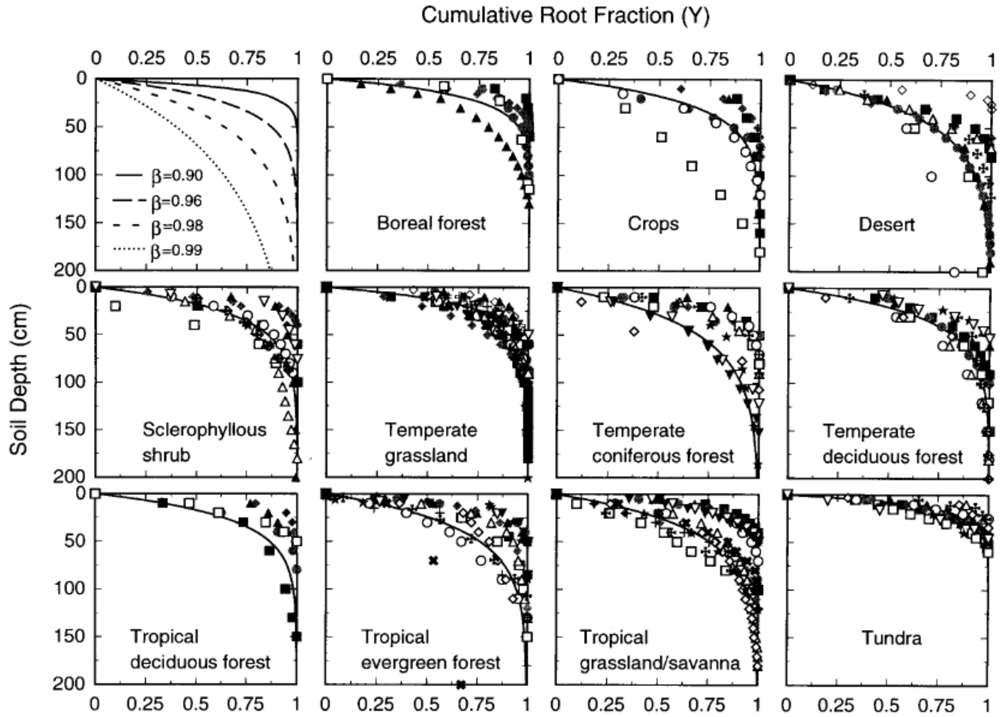


Figure 7. Cumulative root distribution as a function of soil depth for eleven terrestrial biomes. For temperate grassland 83% of root biomass is in the upper 30 cm (Source: Jackson *et al*., 1996).

- Schenk (2008) suggested that several ecological factors favour shallow over deep roots and that root profiles tend to be as shallow as possible. Schenk and Jackson (2002) noted a positive relationship between root depth and annual precipitation for perennial grasses; with shallower depths noted under dry conditions (Figure 8).

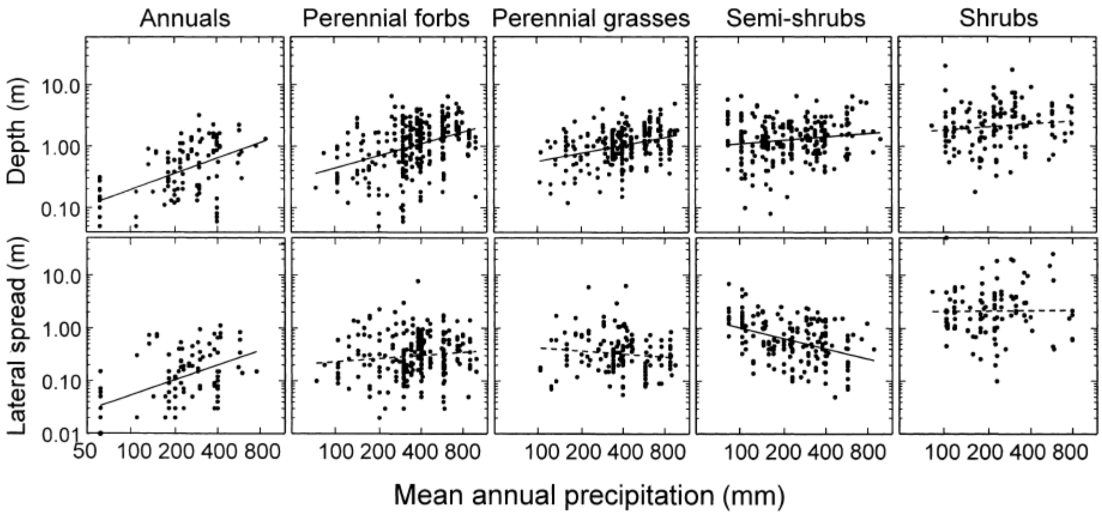
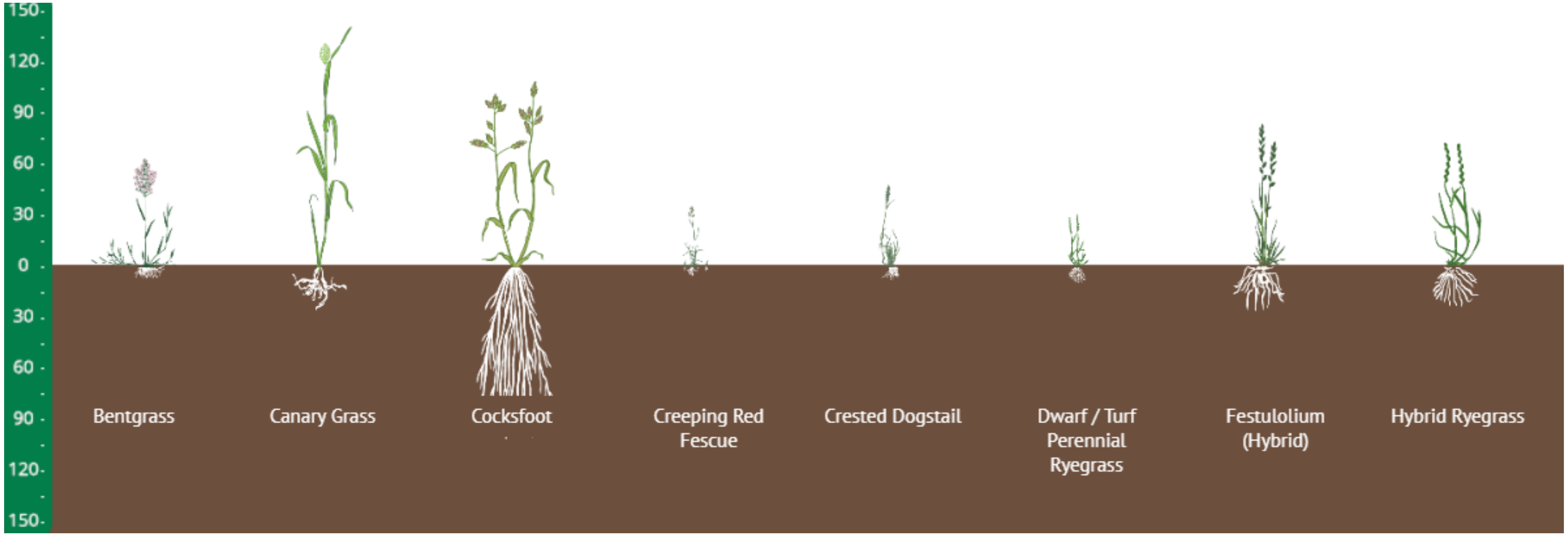
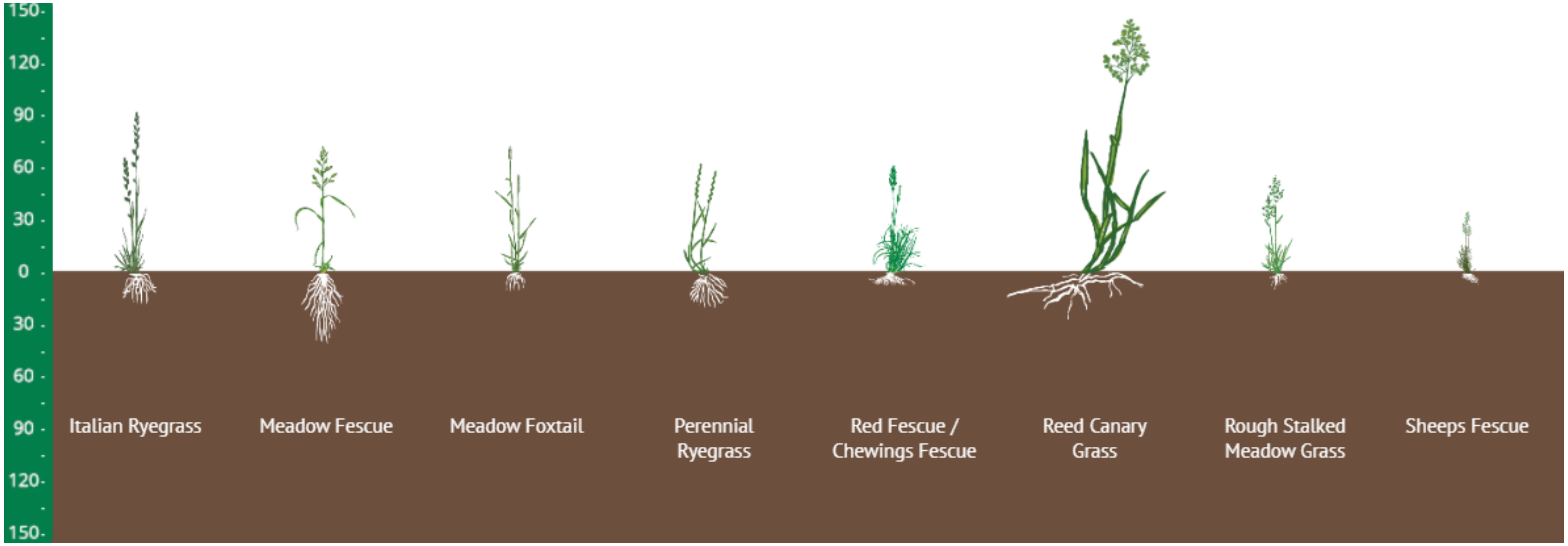


Figure 8. Rooting depth and lateral root spread for five plant growth forms as a function of mean annual precipitation (Source: Schenk and Jackson, 2002).

- Figure 9 (below) illustrates the height and rooting depth/morphology of 23 commonly grown grass species in England and Wales. Of the species detailed, only 3 (<15%) typically root below 30 cm (i.e. Cocksfoot, Meadow Fescue and Tall Fescue). Most species have a similar root morphology, apart from Timothy which has a wide/shallow root distribution.
- Figure 10 and 11, show the height and root depth of other non-legume and leguminous forage plants. The non-leguminous plants mostly root to a depth >1 m; chicory has an extensive root system to >1.5 m, whereas the root system of plantain, although almost as deep, is less dense and is dominated by a central tap root. In comparison, the leguminous plants mostly root to a depth of <60 cm, except for Sainfoin and Lucerne, which both root to >1.5 m. Sainfoin is characterised by a long thin root system, whereas Lucerne has more branched root system. Also, of note is the shallow root depth of many clover species and the stoloniferous spread of the White clover species.


150
120
90
60
30
0
30
60
90
120
150
Bentgrass
Canary Grass
Cocksfoot
Creeping Red Fescue
Crested Dogstail
Dwarf / Turf Perennial Ryegrass
Festulolium (Hybrid)
Hybrid Ryegrass


150
120
90
60
30
0
30
60
90
120
150
Italian Ryegrass
Meadow Fescue
Meadow Foxtail
Perennial Ryegrass
Red Fescue / Chewings Fescue
Reed Canary Grass
Rough Stalked Meadow Grass
Sheeps Fescue

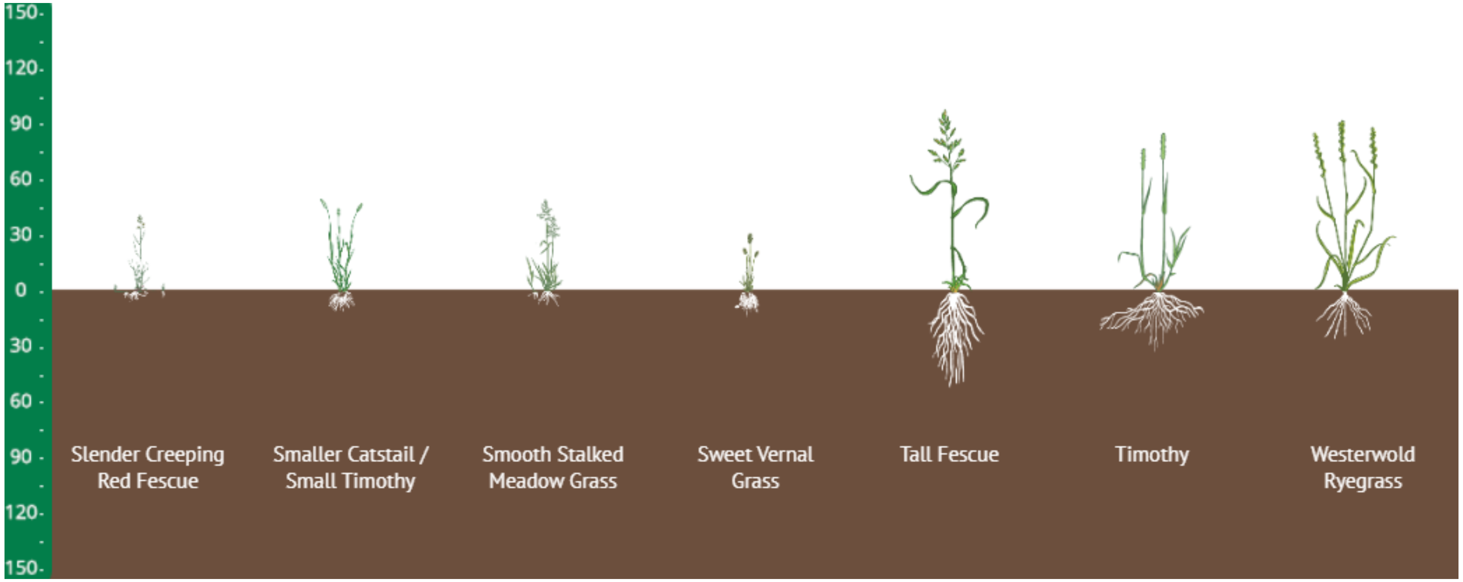


Figure 9. Height and rooting depth/morphology of commonly grown grass species in England and Wales (Source: https://www.cotswoldseeds.com/species-guide.asp).

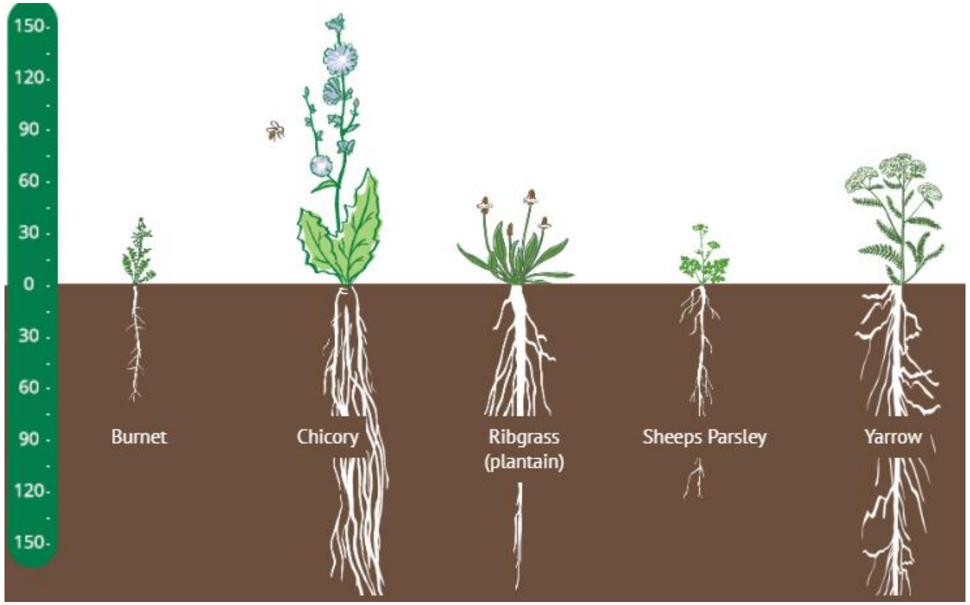


Figure 10. Height and rooting depth/morphology of commonly grown non-leguminous forage species in England and Wales (Source: https://www.cotswoldseeds.com/species-guide.asp).

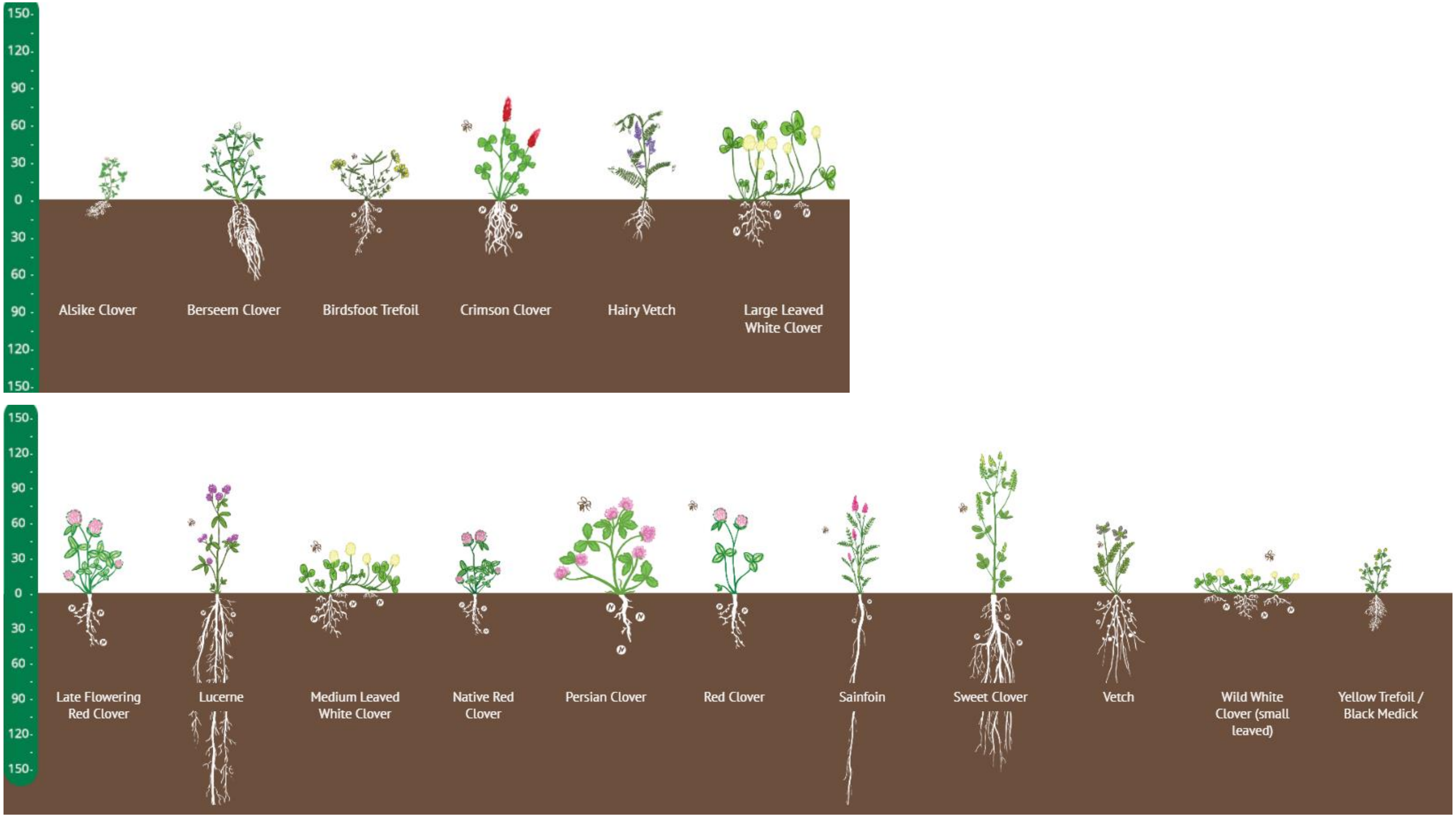


Figure 11. Height and rooting depth/morphology of commonly grown leguminous forage species in England and Wales (Source: https://www.cotswoldseeds.com/species-guide.asp).

8.2 Grass root depth distribution

- Typically, most temperate grassland root systems are found in the top 30 cm of the soil, albeit that some roots may extend to depths of >1m. However, to choose the most suitable grassland species for any situation it is essential to understand any variation in root characteristics.
- Nelson Brown *et al*. (2010) compared the rooting depth and plant height of a variety of grasses native to the US (including PRG, Tall Fescue and Red Fescue). Grasses were grown in a 76 cm length of drainpipe and the percentage of the root mass in each tenth (7.6 cm) of the pipe was recorded after 10 weeks. The experiment was repeated three times with the third experiment running for 14 weeks. Whilst the design of the study does limit the maximum depth of the root it does illustrate the variation in root depth between species. The results showed that the measured root mass was predominately in the top 7.6 cm: PRG 73%, Tall Fescue 63% and Red Fescue 84% (Figure 12). For the longer experiment, 41%, 68% and 60% of the root mass was in the top 7.6 cm for PRG, Tall Fescue and Red Fescue respectively (Figure 13). Although there was some variation in the proportional distribution of the root mass between experiments the results illustrate the shallow rooting depth of many grass species, at least in the early stages of growth.

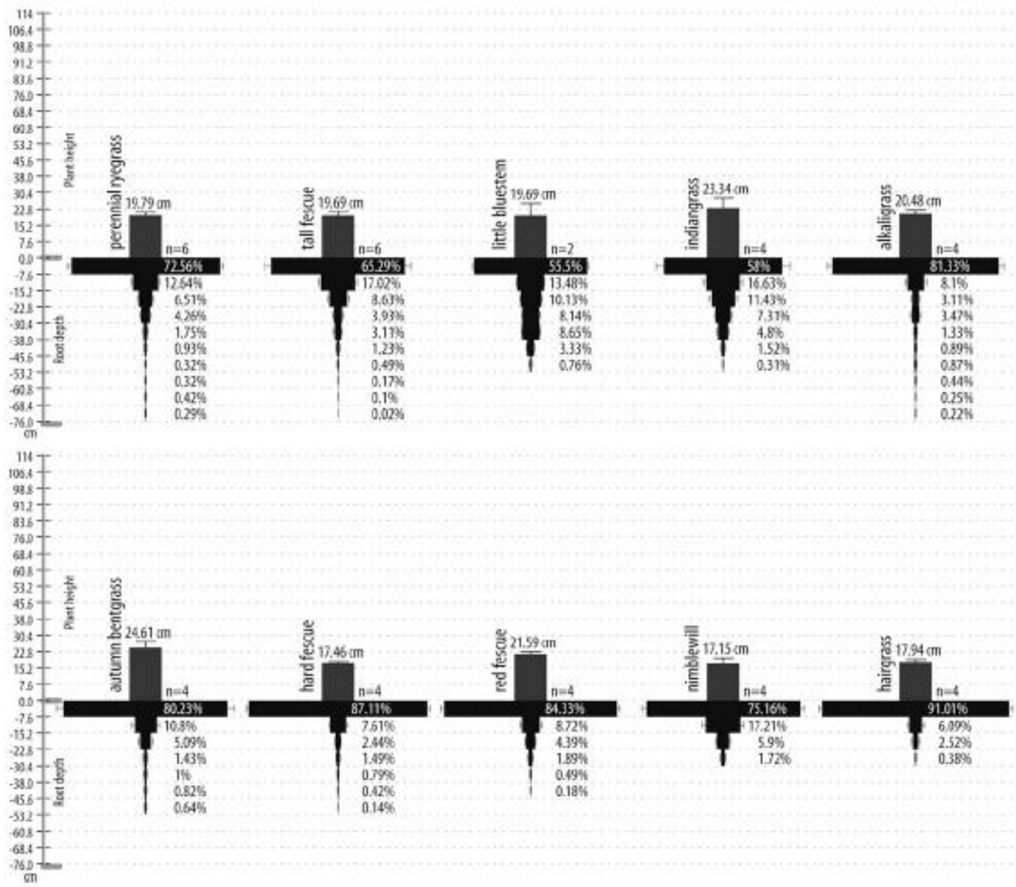


Figure 12. Plant height, root depth and root mass distribution for grass species grown in a rooting column containing four plants (n = number of replicate columns) for 10 weeks. The horizontal bars indicate the percentage of the total root mass at each depth (Source: Nelson Brown *et al*. 2010).

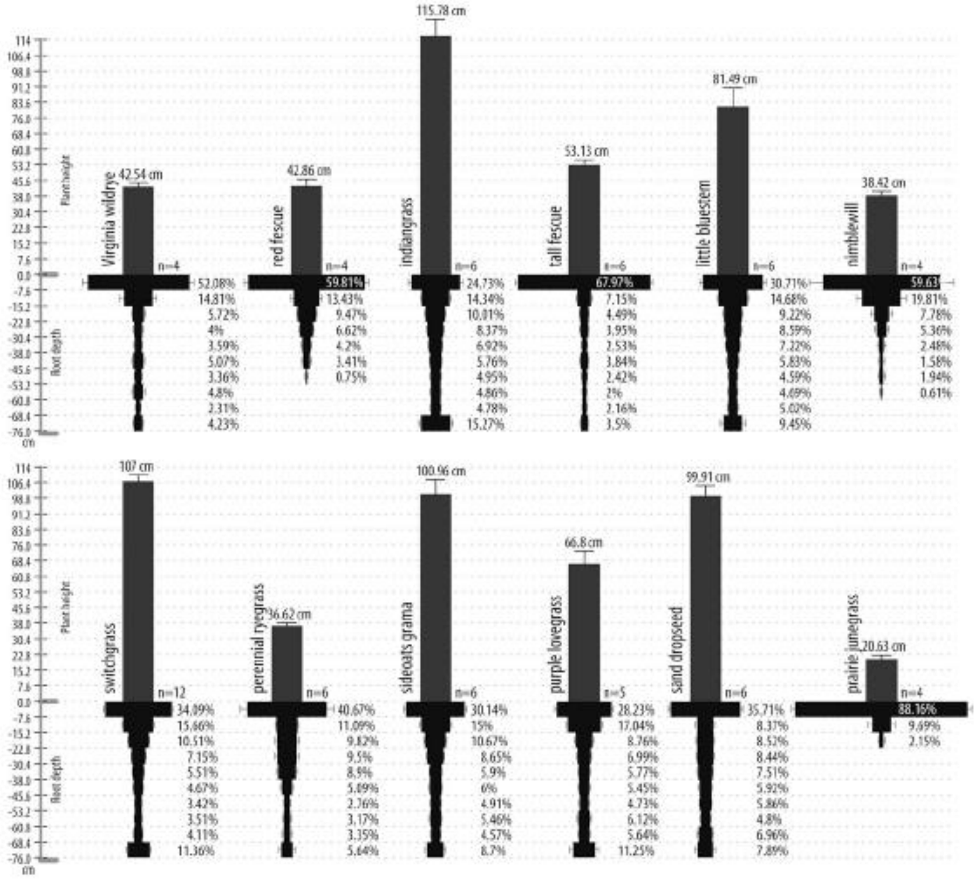


Figure 13. Plant height, root depth and root mass distribution for grass species grown in a rooting column containing four plants (n = number of replicate columns) for 14 weeks. The horizontal bars indicate the percentage of the total root mass at each depth (Source: Nelson Brown *et al*. 2010).

- Fort *et al* (2013), examined the functional traits of roots (including, length, diameter, mass, proportion below 20 cm and fine root %), for eleven temperate perennial grass species under field conditions. The species included, Creeping Bent (*Agrostis capillaris),* Cocksfoot (*Dactylis glomerata*)*,* Red Fescue (*Festuca rubra*)*,* Yorkshire Fog (*Holcus lanatus*)*,* PRG (*Lolium perenne)* and Timothy (*Phleum pratense).* Seeds of each species were collected from natural populations in a central Pyrenean valley (altitude 500-800 m) in France. Plants were grown outside in a clay soil (37.5 ± 5% clay) with a pH of 8.1 from autumn 2004 to March 2010 when four soil cores were removed from the centre of each plot.
- The results showed that Red Fescue and PRG had fewer fine roots (≤50%) than the other four species. Root diameter was highest in PRG (0.15 mm) and lowest in Cocksfoot and Timothy (0.11-0.12 mm). Root mass ranged from ≤250 g/m^2 (Cocksfoot, Yorkshire Fog and Timothy to 565 g/m^2 for Red Fescue, although the large standard deviations indicated that there was some intra species variability, Table 8. The percentage of the root mass below 20 cm ranged from 12 to 23%; with Red Fescue (12%) having the lowest and creeping bent (23%) the most below 20 cm depth (Table 8). However, for all species more than 75% of the root mass was above 20 cm.

Table 8. Mean ± standard deviation of root functional traits (Source: Fort *et al*., 2013).

Species	Fine root % (0-0.1 mm diameter)	Mean root diameter (mm)	Root mass (g/m^2)	Deep root % (mass below 20 cm depth
Creeping Bent	58.7 ± 1.1	0.13 ± 0.00	328 ± 84	23.3 ± 3.4
Cocksfoot	57.9 ± 2.1	0.12 ± 0.00	231 ± 14	14.7 ± 5.8
Red Fescue	47.8 ± 1.1	0.14 ± 0.01	565± 193	12.0 ± 5.2
Yorkshire Fog	60.0 ± 2.2	0.13 ± 0.01	230 ± 15	17.3 ± 6.1
Perennial Ryegrass	50.1 ± 1.6	0.15 ± 0.01	443 ± 109	21.4 ± 0.6
Timothy	59.4 ± 2.0	0.11 ± 0.01	249 ± 73	18.7 ± 12.2

- Cougnon *et al*. (2013) measured the root biomass of diploid perennial ryegrass (PRG) and Tall Fescue in a series of yield trials differing in soil type (sandy loam, sand and loam), location (three in Belgium and one in the Netherlands) and management. Soil cores were taken in spring and in autumn at six or seven depths (between 70 and 90 cm).
- In the upper soil level, no significant differences in root biomass were found between Tall Fescue and PRG (Table 9). Below 15 cm, significant differences between Tall Fescue and PRG occurred at different locations for different depths on the sandy loam and loam soils (Table 9). However, on the sandy soil, no significant differences were found in root biomass between Tall Fescue and PRG (data not shown). A consistently higher root biomass for Fescue compared to PRG was found below 40-45 cm, but over the whole soil profile the root biomass of Fescue was not higher than that of PRG. The authors noted that differences in root biomass were greater under a cutting than a grazing regime.

Table 9. Root biomass (g dry matter/m^2) for *Festuca arundinacea* (Fescue) and diploid *Lolium perenne* (PRG) measured in sandy loam (Melle and Merelbeke) and loam soils (Poperinge). Soil profile 0-90 cm in 15 cm increments. Significance of differences between species indicated as * *P*<0.001; ** *P*<0.01; * *P*<0.05; ns = not significant (Source: Cougnon *et al*., 2013).**

Trial	Species	0-15 cm	15-30	30-45	45-60	60-75	75-90	0-90
		cm						
Melle A	Fescue	1082 [80%]	167	47	30	18	10	1,351
	PRG	846 [77%]	183	32	15	11	6.	1095
		ns	ns	ns	ns	ns	ns	ns
Melle B	Fescue	763 [74%]	109	49	37	37	37	1,032
	PRG	812 [75%]	163	40	32	24	13	1,083
		ns	ns	ns	ns	ns	*	ns
Melle C	Fescue	731 [71%]	143	60	39	37	26	1,036
	PRG	894 [81%]	118	35	28	14	14	1,103
		ns	ns	ns	ns	*	ns	ns
Merelbeke	Fescue	841 [66%]	181	113	55	42	38	1,271
	PRG	509 [74%]	107	55	13	2	1	685
		ns	*	*	*	*	ns	*
Poperinge	Fescue	742 [74%]	72	53	59	46	29	1,000
	PRG	692 [87%]	62	24	13	5.	2	799
		ns	ns	ns	*	**	***	ns

- Nie *et al*. (2008) carried out field experiments at seven sites in Australia from 2002 to 2006 which included measurements of root characteristics (depth and root density) for Cocksfoot, Tall Fescue, PRG and Plantain. The authors noted significant differences in rooting depth between species and cultivars (*P*<0.001); Tall Fescue had a mean root depth >1m, compared with <1 m for the other species. There was no significant difference in root density between species and cultivars in the topsoil; however, there were differences (*P*<0.01) in the subsoil (0.1–1.1 m) and deeper subsoil (1.1–2.0 m). Tall Fescue (*cv. AU Triumph*) had >6,000 roots/m^2 in the subsoil and >290 roots/m^2 in the deeper subsoil. In comparison, the root systems of Cocksfoot, Perennial Ryegrass and Plantain were less dense both in the subsoil (3,941–4,504 roots/m^2) and deeper subsoil (0-43 roots/m^2) (Table 10).

- A comparison of root density at different depths showed that 60-80% of roots were in the 0-30 cm soil depth for Cocksfoot, 60-70% for Tall Fescue and 70-80% for PRG; for all three species *c*.40% of roots were in the top 0-10 cm.

Table 10. Predicted means of root density (roots/m^2) for various pasture cultivars between 0 and 0.1 m (topsoil), 0.1 and 1.1 m (subsoil) and 1.1 and 2 m (deeper subsoil) and mean rooting depth (m) (Source: Nie *et al.,* 2008).

Species and Cultivar	**Topsoil (0-0.1 m)**	**Subsoil (0.1-1.1 m)**	**Deeper subsoil (1.2-2 m)**	**Mean rooting depth (m)**
Cocksfoot (*cv. currie*)	14,201	4,504	0	0.97
cv. Porto	14,024	3,941	0	0.91
Tall Fescue (*cv. Fraydo*)	14,126	4,415	122	1.09
cv. Resolute Max P	14,884	4,643	109	1.17
cv. AU Triumph	13,979	6,278	293	1.18
PRG (c*v. AVH 4*)	14,434	4,341	0	0.90
cv. Avalon	13,549	4,240	43	0.99
Plantain (c*v. Tonic*)	13,782	3,830	58	0.97

- Crush *et al*., 2010, selected four perennial ryegrass groups according to rooting pattern (1) low surface (0-10 cm) root mass and roots to 1 m; (2) high surface root mass and roots to 1 m; (3) high root mass 10-20 cm and roots to 1 m; (4) high surface root mass, shallow rooting. Progeny of each group were planted into 1 m deep root screening tubes and a range of shoot and root parameters were determined. The results showed that that the vertical distribution of the root mass was true to type after one cycle of selection (Figure 14).

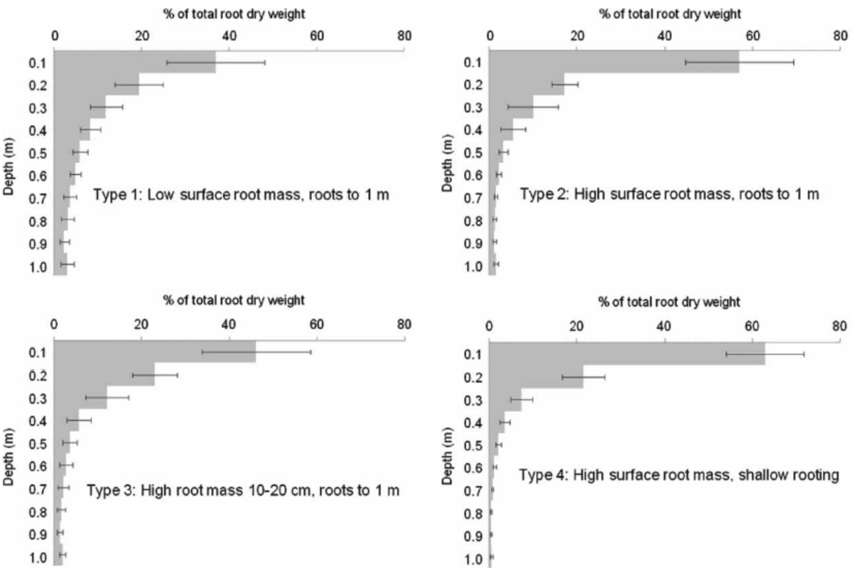


Figure 14. Root dry weight distribution for four genotypes for PRG. Values are ± standard deviation (n=36 for type 1, n=20 for type 2 and n=24 for type 3 and 4) (Source: Crush *et al*., 2010).

- Van Eekeren *et al*. (2010) grew Tall Fescue, Cocksfoot and PRG either as monocultures or in mixtures to study the effect on yield and root biomass. Grass yield was highest in the PRG/Cocksfoot mix (16.4 t/ha dry matter) and lowest in the PRG (13.8 t/ha dry matter) monoculture (PRG/Cocksfoot mix > Cocksfoot > Tall Fescue > PRG/Tall Fescue mix >PRG). Root biomass was significantly higher in PRG, Tall Fescue and PRG/Tall Fescue mix (>5 t/ha ash free dry matter-AFDM) than in the Cocksfoot and PRG/Cocksfoot mix treatments (<4 t/ha AFDM). PRG, Fescue and PRG/Fescue mix had a higher root biomass in the 0–10 cm than Cocksfoot and PRG/Cocksfoot mix (Figure 15). Tall Fescue had the highest root biomass in the 10–20 and 20–30 cm soil layer of all grass treatments.

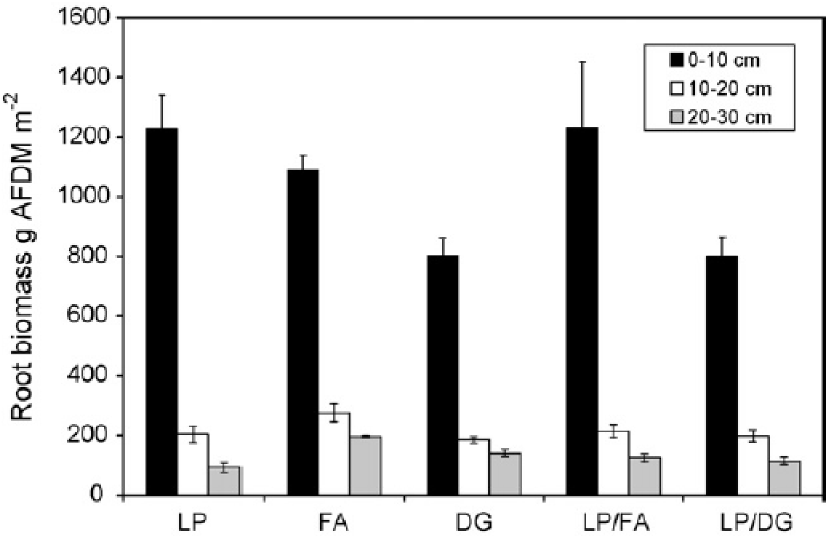


Figure 15. Root biomass (g ash free dry matter AFDM) in grassland with *Lolium perenne* (LP) *Festuca arundinacea* (FA), *Dactylis Glomerata* (DG), a mixture of LP/FA and of LP/DG at three soil depths (0-10, 10-20 and 20-30 cm) (Source: van Eekeren *et al*., 2010).

- The higher root biomass of PRG and Fescue compared to Cocksfoot and the distribution of roots over the soil layers was in line with results reported by Garwood and Sinclair (1979). Although Cocksfoot is commonly regarded as a drought-resistant species, the authors did not find evidence that it was deeper-rooted or more effective in its exploitation of soil water than PRG.

8.3 Clover

- Studies on the root depth distribution of White Clover report that up to 70% of the total root mass occurs in the top 10–15 cm of the profile (Caradus, 1991; Nichols *et al*., 2007). Studies have shown that uptake of water and nutrients is influenced by root diameter, with greater efficiency of uptake in fine roots due to a higher ratio of root surface area to soil volume (Eissenstat, 1992).
- Nichols *et al* (2016) grew two White Clover cultivars (*Trifolium. repens*), two *T. uniflorum* cultivars (perennial wild species that occurs in dry and nutrient poor environments) and two *T. repens* x *T. uniflorum* backcross hybrids in 1 m deep x 0.15 m diameter tubes of sand culture (10 per treatment). Tubes were irrigated with a low ionic strength nutrient solution based on the typical soil solution of New Zealand pasture topsoils. Traits related to root depth distribution

were compared in plants harvested 70, 119, 170 and 237 days after sowing and root weight was determined at 5 cm depth increments to 20 cm and then in 10 cm increments to 1 m.

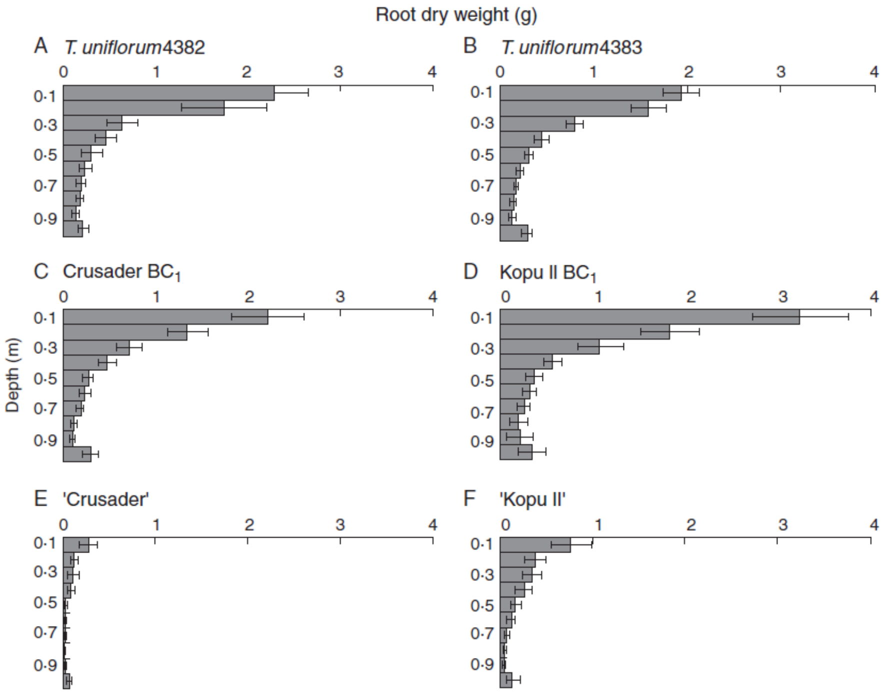


Figure 16. Root depth distribution at harvest (237 days after sowing) for *T. uniflorum* (4382 and 4383), *T. repens* x *T. uniflorum* backcrosses (Crusader BC1 and Kopu II BC1) and T. repens (Crusader and Kopu II) (Source: Nichols *et al*., 2016).

- Root system shape of the hybrids was more like *T. uniflorum* than White Clover (Figure 16). The hybrids and *T. uniflorum* had a higher rate of decrease in root mass with depth than White Clover, resulting in a higher proportion of root mass in the upper profile. Percentage total root mass at 100–200 mm depth was higher for *T. uniflorum* than White Clover. Roots of the hybrids and *T. uniflorum* also penetrated deeper than those of White Clover. T. *uniflorum* had thicker roots at 50–100 mm deep than the other types, and more of its fine root mass at 400–500 mm. The hybrids and White Clover had more of their fine root mass in the topsoil. The authors concluded that the rooting characteristics of White Clover could be altered by hybridisation with T. *uniflorum*, which would potentially improve water and nutrient uptake and drought resistance.

9 Effect of drought on grass and forage species

- Changes in temperature and rainfall pattern are likely to impact on crop yields and quality and may affect the viability of existing rain-fed crops. Climate change predictions suggest that whilst total rainfall volumes will remain relatively unchanged the pattern will change resulting in wetter winters and drier summers. Grass growth is restricted by drought and drier summers are likely to limit grass growth especially on soils with low soil available water in the summer months (St. Clair *et al*., 2009).
- Where there is sufficient water and nutrient supply, grassland productivity could benefit from future climatic scenarios, i.e. higher CO_2 concentrations, higher temperatures and longer vegetation periods (Lüscher *et al*., 2005). However, water availability during the vegetation growing season is likely to be limited under future climatic predictions (Buttler *et al*., 2019). For central Europe, for example, it is predicted that the occurrence of dry summers will increase by the year 2050 (IPCC, 2013) and that extreme drought events could become more frequent and intense in response to climate change (Ciais *et al*., 2005).
- The response of grasslands to drought and the degree to which ecosystem services are affected depend on the complex interactions among different factors involving plant community diversity, soil properties, climatic conditions and land management (Deléglise *et al*., 2015; Thébault *et al*., 2014). Furthermore, duration, intensity and timing of drought, and the frequency of rainfall events are important factors influencing the response of grassland communities to lack of water (Chou *et al*., 2008; Didiano *et al*., 2016).
- Grass species characterized by longer roots, which allow them stronger soil penetration to gain access to the deeper sources of water are better adapted to dry environments. In contrast species growing in areas with a mild climate and in favourable water conditions have a widely extensive root system (Ho *et al*., 2005). It has also been shown that plants producing strong root systems in the early stage of the vegetative season are in an excellent position to maintain turgor during drought limiting the effects on dry matter yields (Lynch, 2007).
- To obtain maximum above-ground production, large root systems are often not required if water and nutrients are continuously available. When this condition is not met, however, larger root systems may reduce the impact of variations in nutrient and water supply (Noordwijk and Willigen, 1987). Consequently, targeting selection of species with functional traits that allow them to cope with drought stress will increase the resilience of grass swards. Authors have shown that deep rooted species have increased drought resistance (Skinner *et al*., 2004), reflecting their ability to acquire water from deeper soil layers.
- Grasslands of low to medium management intensity have shown resilience to drought (Vogel, *et al*., 2012; Hoover *et al*., 2014) as reduced growth is sufficient to meet animal intake. However, for intensive grassland management, high resilience is required to ensure sufficient grass growth to meet feed requirements either by grazing or by cutting.
- Combining selected species in grassland mixtures under ambient climatic conditions can result in higher yields than where single species are grown, due to niche complementarity and positive interspecific interactions (Kirwan *et al*. 2007). High over yielding (ratio of mixture to monoculture yield of >1) has recently been demonstrated in intensively managed grass–legume mixtures over largely differing climatic zones from Mediterranean to Nordic regions (Finn *et al*. 2013).
- It has been suggested that soil water in deeper soil layers might not facilitate drought resistance of deep-rooted species because grassland species under drought do not necessarily take up water from deeper soil layers (Hoekstra *et al*. 2014; Prechsl *et al*. 2015). Accessing water from

deeper layers comes with a trade-off between water and nutrient availability. Generally, more water is available in deeper soil layers however nutrient concentration decreases considerably with increasing soil depth (Dolan *et al*. 2006) especially in fertilised agricultural systems. The benefit of accessing water from deeper soil layers may thus be counteracted by lower nutrient availability. Results reported by Hoekstra *et al*. 2015 and Hofer (2016), suggest that although deep rooting might contribute to drought resistance, the effect could be small and might become important only under extreme drought conditions.

9.1 Some examples of species response to drought

- Skinner and Comas, 2010, examined the rooting characteristics (to a depth of 50 cm) for 21 forage species (including Cocksfoot, Tall Fescue, PRG, Timothy, Red and White Clover, chicory, plantain and Birdsfoot trefoil) in a greenhouse study. Plants were exposed to drought or low N conditions and measurements of root biomass, root depth, and root depth distribution were made.
- The authors noted that PRG and Timothy showed significant decreases in root biomass in response to drought stress (whereas plantain increased root biomass), Figure 17. Drought stress increased partitioning to roots for seven species including Birdsfoot Trefoil, Red Clover, White Clover and plantain.
- Drought stress had no effect on the proportion of deep roots for forbs (herbaceous flowering plants that are not grasses, sedges or rushes) and legumes, but significantly increased the proportion of deep roots (in the 30-40 cm layer) for grasses to 15% ($P<0.01$). All grass species tended to increase the proportion of deep roots under drought stress, but the increase was significant for Cocksfoot, PRG and Timothy.

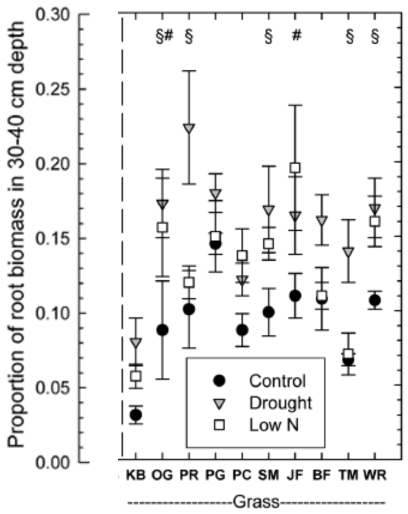


Figure 17. Total root biomass for 10 perennial grasses harvested 35 d after transplanting into 50 cm deep PVC pots. Species abbreviations: Kentucky bluegrass, KB; orchard grass (Cocksfoot), OG; perennial ryegrass, PR; prairie grass, PG; reed canary grass, PC; smooth brome, SM; 'Jessup MaxQ' Tall Fescue, JF; 'Barolex' Tall Fescue, BF; Timothy, TM; Virginia wild rye, WR. Error bars indicate ± 1 SE. § indicates significant difference between drought and control plants at *P* = 0.05. # indicates significant difference between low N and control plants at *P* = 0.05 (Source: Skinner and Comas, 2010).

- Zwicke *et al*. (2015) compared root and shoot characteristics of six perennial species (including Cocksfoot and Tall Fescue) from upland grasslands and one Mediterranean drought resistant grass species (a Mediterranean cultivar of Cocksfoot) under irrigation (maintaining soil water content near field capacity), summer drought (50 days, 20 days of gradual soil drying followed by 30 days at soil water content of <0.1m^3/m^3) and after re-wetting. Grass seeds were grown in tubes (12 per species each 150 cm deep, 10 cm diameter) filled with soil (12% clay, 59% sand, 13% organic matter) from an upland grassland. Following the drought treatment, the tubes were watered and maintained at field capacity until the growing season ended. The following year (until June), all tubes received rainfall according to local conditions (average annual precipitation 579 mm).
- Baseline data (i.e. before drought) showed that all three species had a maximum rooting depth of >1 m and a similar root mass; there was little change in these parameters after moderate or severe drought (Table 11). The root resilience index, estimated as the ratio of spring standing root mass measured 1 year after drought and spring standing root mass measured before drought, was close to one, except for the two cultivars of Cocksfoot(P<0.05), which showed the highest values (suggesting a high drought tolerance). The authors suggested that dehydration avoidance through water uptake was associated with species that had deep roots (>1.2 m) and high root mass (>4 kg/m^3).

Table 11. Root depth parameters for Cocksfoot and Tall Fescue grasses before drougth and after moderate and severe drought (Source: Zwicke *et al*., 2015).

Conditions/plant species	Max root depth (cm)	95% rooting depth (cm)	Root mass (kg/m^2)
Before drought			
Cocksfoot	122	71	4.6
Cocksfoot (Mediterranean)	134	82	4.9
Tall Fescue	146	106	5.0
Moderate drought			
Cocksfoot	134	67	4.7
Cocksfoot (Mediterranean)	129	74	5.9
Tall Fescue	147	98	4.9
Severe drought			
Cocksfoot	136	67	4.9
Cocksfoot (Mediterranean)	133	78	5.3
Tall Fescue	150	93	5.0

- Wedderburn *et al*. (2010) investigated root growth patterns in five different ryegrass cultivars grown outdoors under simulated field edaphic conditions including drought. Soil moisture was always kept at non-limiting levels prior to the drought treatment in 1995. Over the first 2 years of the experiment, when there was no moisture stress, all the ryegrasses displayed very similar temporal patterns for total root counts. On average, only 21% of root counts were recorded below 7 cm depth.
- The percentage of root counts at each sample depth, changed over time in the well-watered treatment. As the swards aged, there was a change in the proportion of root numbers found down the soil profile with less counted in the shallow layers and more at depth. The drought

treatment was characterised by a low percentage of roots in the top 4 cm of soil and a greater percentage of roots at 5-20 cm than in the watered treatments (Figure 18).

- The summer drought resulted in an increase in root counts right down the profile, which started about a month after the drought began. This was followed by rapid death of roots in the top 15 cm of soil but lower death rates deeper in the soil. After rewetting of the soil, there was a delay of approximately 1 month before a rapid increase in root production occurred.

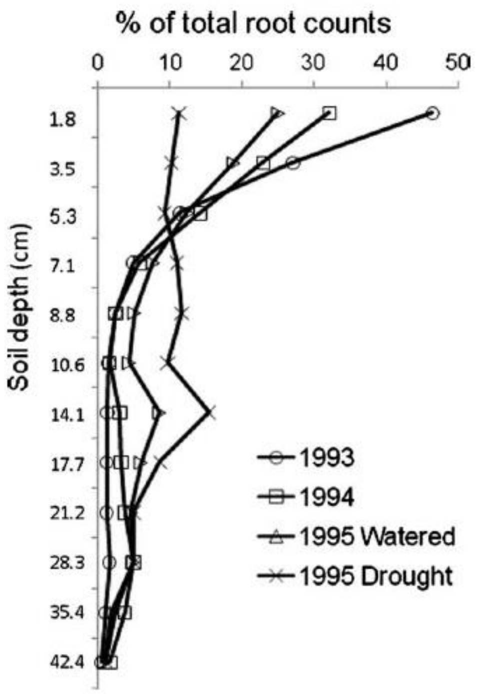


Figure 18. Average distribution of root counts for the five ryegrass cultivars (% of total counts) for the well-watered treatments in 1993, 1994 and 1995 and the summer drought stressed treatment in 1995 (Source: Wedderburn *et al*., 2010).

10 ALC and drought

- The changing pattern of rainfall (i.e. wetter winters and drier summers) is likely to affect grassland productivity. Grass growth is restricted by drought and drier summers are likely to limit grass growth especially on soils with low soil available water in the summer months (St. Clair *et al*., 2009). Drought may also increase the risk of wildfires affecting extensive grazing areas. Conversely, wetter winters may cause waterlogging which would increase the risks of soil damage by poaching reducing opportunities for overwinter grazing (Thomas *et al*., 2010).
- Grass growth begins above a minimum temperature (5.5°C) and is stimulated by warmer weather, provided there is sufficient soil moisture. Warmer temperatures will increase the length of the grazing season (IGER, 2003) with grass production starting earlier in the spring and continuing later in the autumn (Thomas *et al*., 2010). However, as grass yields improve with warmer conditions, they are also vulnerable to reduced soil moisture availability during drought (Brown *et al*., 2016).
- Studies have shown that grassland ecosystems can adapt to extreme events (Vicente-Serrano *et al.,* 2012) including physiological adaptations to overcome the challenges of drought stress (Craine *et al.,* 2013) and wildfire (Bond *et al*., 2005, Bond and Keeley 2005, Nano and Clarke, 2011). This may limit the effect of climate change on grasslands and several authors have noted that anticipated impacts of climate change on grassland dry matter yield are small. For example, the model used by Qi *et al*. (2018) predicted that by 2050, yield under the UKCP09 medium emission scenario would increase to 15.5 and 9.9 t/ha on temporary and permanent grassland, respectively (from 12.5 and 8.7 t/ha) and no significant change in the yield of rough grassland was predicted (2.8-2.7 t/ha). However, any dry matter yield increases will depend on other interacting factors such as soil N fertility (Daepp *et al*., 2001), water supply and soil water stress (Deryng *et al*., 2016).
- The ALC droughtiness criteria method is based on an estimation of the average soil moisture balance for two reference crops (potatoes and wheat) at a given location. Moisture balance is calculated from two parameters: 1, the crop-adjusted available water capacity of the soil profile (AP) and 2, moisture deficit (MD). As the climate gets warmer and drier in the summer the drought factor becomes more limiting to crop productivity.

10.1 Calculation of crop adjusted soil available water capacity.

- The total amount of soil water available to plants is the volumetric soil water content between 0.05 and 15 bar suction (or for sands and loamy sands between 0.10 and 15 bar suction). These suctions approximate to field capacity defined as the point at which the soil moisture deficit is zero, i.e. when all soil pores other than those that drain under gravity are full of water and wilting point (when the plants can extract no more moisture from the soil). As laboratory measurements of available water are time consuming and expensive, the ALC includes tabulated values based on combinations of soil textures and structure (reproduced in Table 12, below).

Table 12. ALC estimation of available water (%) from texture class, horizon and structural condition (Source: MAFF, 1988).

Texture Class	Topsoil TA_v	Subsoil TA_v (EA_v in brackets)		
		good	*moderate*	*poor*
Clay	17	21 (15)	16 (8)	13 (7)
Silty clay	17	21 (15)	15 (8)	12 (7)
Sandy clay	17	19 (14)	15 (10)	13 (8)
Sandy clay loam	17	19 (14)	15 (10)	13 (8)
Clay loam	18	21 (14)	16 (10)	12 (7)
Silty clay loam	19	21 (12)	17 (10)	12 (6)
Silt loam	23	23 (17)	22 (14)	15 (9)
Fine sandy silt loam	22	22 (16)	21 (15)	15 (9)
Medium sandy silt loam	19	19 (13)	17 (11)	15 (9)
Coarse sandy silt loam	19	23 (17)	19 (11)	15 (7)
Fine sandy loam	18	22 (17)	18 (13)	17 (11)
Medium sandy loam	17	17 (13)	15 (11)	11 (8)
Coarse sandy loam	17	22 (15)	16 (11)	11 (8)
Loamy fine sand	18	15 (13)	15 (13)	*
Loamy medium sand	13	12 (9)	9 (6)	*
Loamy coarse sand	11	11 (7)	8 (6)	*
Fine sand	*	14 (12)	14 (12)	*
Medium sand	12	7 (5)	7 (5)	*
Coarse sand	*	5 (4)	5 (4)	*
Marine light silts[2]		33 (30)	28 (22)	*
All Horizons				
Organic sands			23 (16)	
Organic loams			28 (20)	
Organic clays			23 (16)	
Peaty sands			39 (36)	
Peaty loams			27 (18)	
Sandy peats			45 (30)	
Loamy peats			35 (26)	
Humified peats			33 (24)	
Fibrous and semi-fibrous peats			44	

- The amount of soil water available to a crop depends on both soil properties and crop rooting patterns. Thomasson (1979) defined the soil available water to plants (SWAP) as the total amount of water that can be extractable by the roots of different crop plants. Figure 19 is a graphical representation of the simplified crop rooting models originally proposed by Thomasson (1979). They are based on idealised rooting depth patterns for arable crops (grass, cereals, sugar beet and potatoes) in northern Europe. The models consider the fact that a high proportion of plant roots, in some cases as much as 70%, is found in the upper part of the soil profile (0–50cm). These roots are normally able to extract all the water held by soil particles in the range 0.05-15 bar. However, plant root densities are often much smaller in the deeper subsoil (e.g. >50cm depth where, in practice, only the easily available water (0.05-2.0 bar) is extractable.

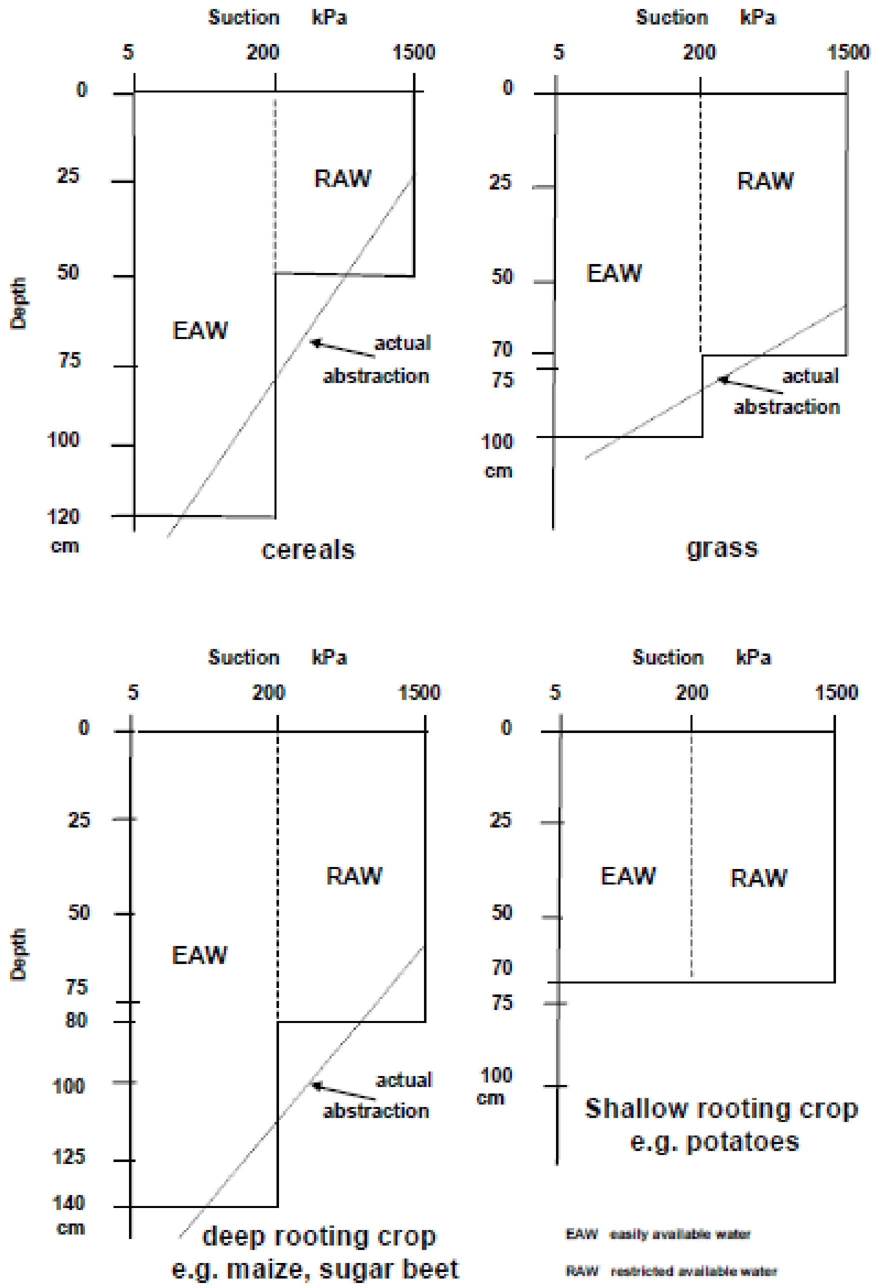


Figure 19. Root abstraction models for temperate arable crops in northern Europe.

NB. EAW: easily available water, water held at 0.05-2.0 bar; RAW: restricted available water, water held at 2-15 bar; TAW: total available water is EAW + RAW. Source: Jones *et al.* (2000) based on Thomasson (1979).

- In line with Thomasson (1979) the guidance in the ALC assumes that under favourable conditions cereals will root to about 120 cm and potatoes will root to 70 cm. However, the root systems of cereals are less well developed below 50 cm and so are less able to extract water beyond that depth. Below 50 cm, it is assumed that for cereals only the volume of easily available water (held in the soil between 0.5 and 2.0 bar suction) is extracted. There is currently no guidance in the ALC for calculating crop adjusted water capacity for grass. Thomasson (1979) suggests that the soil water available to permanent grass should be calculated to 100 cm considering the total available water (0.05-15 bar) to 70 cm and the easily available water (0.05-2.0 bar) from 70-100 cm (Figure 19).

- To calculate the ALC crop adjusted soil available water capacity (AP) (mm) for wheat or potatoes the total available water (TA_v) or easily available water (WA_v) of each soil layer is multiplied by its thickness. For wheat, the value of each layer is added to a depth of 120 cm and adjusted using EA_v as applicable; for potatoes no adjustment using EA_v.is required. Figure 20 illustrates the calculations of crop adjusted available water capacity (AP) for both wheat and potatoes.

$$\text{AP wheat (mm)} = \frac{TA_{vt} \times LT_t + \Sigma\,(TA_{vs} \times LT_{50}) + \Sigma\,(EA_{vs} \times LT_{50\text{-}120})}{10}$$

TA_{vt} is Total available water (TA_v) for the topsoil texture.

TA_{vs} is Total available water (TA_v) for each subsoil layer.

EA_{vs} is Easily available water (EA_v) for each subsoil layer.

LT_t is thickness (cm) of topsoil layer.

LT_{50} is thickness (cm) of each subsoil layer to 50 cm depth.

$LT_{50\text{-}120}$ is thickness (cm) of each subsoil layer between 50 and 120 cm depth.

Σ means 'sum of'.

$$\text{AP potatoes (mm)} = \frac{TA_{vt} \times LT_t + \Sigma\,(TA_{vs} \times LT_{70})}{10}$$

LT_{70} is thickness (cm) of each subsoil layer to 70 cm depth

Figure 20. ALC calculation of crop adjusted soil available water capacity-AP (mm) for wheat and potatoes.

- Further adjustments to the values are made to account for the presence of stones rock or a very poorly structured horizon.

10.2 Crop adjusted soil available capacity for grass.

- Table 13 shows the calculated crop adjusted soil available water capacity for grass for four soil textures (clay, clay loam, medium sandy loam and sandy loam) based on the rooting model of Thomasson (1979). Topsoil depth is assumed to be 0-15 cm and sub-soil depth 15-100 cm; the topsoil TAv (Table 13) has been used for the 0-15 cm layer, the subsoil TAv for the 15-70 cm layer and the sub-soil EAv for the 70-100 cm layer. Overall, there is little variation in the AP grass (c.140 mm) except for the medium sand soil which is almost half of the other values (c.70 mm).
- The Thomasson (1979) model was designed for permanent pasture and based on data current in 1979 thus it is questionable how appropriate it is for use with modern varieties or ley grass.

Based on rooting depth data (in Section 8), most grass roots are predominately shallow, extending to ≤ 30 cm (e.g. 40% are in the top 10 cm and >80% in the top 30 cm), albeit that there is some variation between species. However, a small proportion of the roots of many species will extend to depths greater than 30 cm. This suggests that the Thomasson (1979) model depths may not adequately represent many present day grass varieties. For example, for the ryegrass species, which predominate in many improved pasture, AP grass (mm) could be calculated based on TA_v to a depth 15 cm and based on EA to a depth of 1 m, to account for the sparse root system below 15 cm. (Table 14). For all four soil types, the AP grass is reduced when the modified method is used.

Table 13. Crop adjusted soil available water capacity (AP) for grass in clay, clay loam, medium sandy loam and medium sand soil. Based on the method of Thomasson (1979).

Soil	**Depth**	**TA**	**EA**	**Calculation**	**Total AP**
a) grass					
Clay (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	17%		150 x 17% = 26 mm	138 mm
Subsoil 1	15-70	16%		550 x 16% = 88 mm	
Subsoil 1	70-100		8%	300 x 8% = 24 mm	
Clay loam (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	18%		150 x 18% = 27 mm	145 mm
Subsoil 1	15-70	16%		550 x 16% = 88 mm	
Subsoil 1	70-100		10%	300 x 10% = 30 mm	
Medium sandy loam (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	17%		150 x 17% = 26 mm	142 mm
Subsoil 1	15-70	15%		550 x 15% = 83 mm	
Subsoil 1	70-100		11%	300 x 11% = 33 mm	
Medium sand (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	12%		150 x 12% = 18 mm	72 mm
Subsoil 1	15-70	7%		550 x 7% = 39 mm	
Subsoil 1	70-100		5%	300 x 5% = 15 mm	

Table 14. Crop adjusted soil available water capacity (AP) for grass in clay, clay loam, medium sandy loam and medium sand soil.

Soil	Depth	TA	EA	Calculation	Total AP
a) grass					
Clay (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	17%		150 x 17% = 26 mm	94 mm
Subsoil 1	15-100		8%	850 x 8% = 68 mm	
Clay loam (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	18%		150 x 18% = 27 mm	112 mm
Subsoil 1	15-100		10%	850 x 10% = 85 mm	
Medium sandy loam (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	17%		150 x 17% = 26 mm	120 mm
Subsoil 1	15-100		11%	850 x 11% = 94 mm	
Medium sand (to 1 m depth. Subsoil condition moderate)					
Topsoil	0-15	12%		150 x 12% = 18 mm	61 mm
Subsoil 1	15-100		5%	850 x 5% = 43 mm	

10.3 ALC Soil moisture deficit calculation

- The calculation of the soil moisture deficit is a key component of assessing soil droughtiness for ALC. Moisture deficit represents the balance between rainfall and evapotranspiration. The concept of potential evapotranspiration (PE) was defined by Penman (1948) as the water transpired by a short green crop, such as grass, which completely covers the ground and is amply supplied with water to its roots. Given these conditions PE varies with meteorological conditions. PE varies less than rainfall and so rainfall has a greater impact on moisture deficit. For periods when PE exceeds rainfall (R) the potential soil moisture deficit (PSMD) can be calculated as PSMD = ∑ (R-PE); R-PE is calculated daily and summed for a defined period.
- In developing a moisture deficit dataset for ALC two estimates of maximum PSMD were used:
    1. Median max PSMD, PSMDM, 1961-1980 from daily moisture balance of R-PE at 94 agromet stations according to the MORECs system
    2. Mean max PSMD, PSMDS, 1961-75 from monthly moisture balances of R-PT at 970 stations with the same rainfall as 1 but using PT from the pre-MORECs version of the Penman equation.
- Jones (1987) reported multiple linear regression of both estimates of PSMD on accumulated temperature and annual summer rainfall. The variables that best estimated PSMD (for both methods) were average summer rainfall (ASR) and average accumulated summer temperature above 0°C (April to September), accounting for 85% (PSMDS) and 75% (PSMDS) of the variation. The addition of extra variables (altitude, latitude and longitude) slightly increased the precision of the estimate for PSMDS not for PSMDM. The ASR data was log transformed as the data showed a skewed distribution.
- Potential deficits under grass are greater than for arable crops which do not attain full ground cover early in the growing season. Hence, for calculating ALC grade, the PSMD is adjusted for two reference crops, winter wheat and main crop potatoes, which are considered

representative of a broad range of crops in terms of their susceptibility to drought. Crop adjusted MDs are smaller than PSMD so that during a dry June or July where several crops are growing in the same soil type, soil moisture deficits follow the sequence root crops < cereals < grass.

- ALC guidance suggests that the crop-adjusted moisture deficit under winter wheat and main crop potatoes can be calculated by one of two existing methods: 1) the moisture balance method and 2) the rainfall/temperature method. In the first method, the PSMD is adjusted as follows to give MD values for wheat and potatoes:
  - MD (winter wheat) = mid-July PSMD-1/3 April PSMD
  - MD (potatoes) = August PSMD – 1/3 June PSMD – 1/3 mid-May PSMD.
- Alternatively, MD (winter wheat) and MD (potatoes) can be calculated based on relationships between annual summer rainfall (ASR, April to September) and accumulated summer temperature (ATS, April to September) from c.80 weather stations across England and Wales (11. weather stations were excluded from the final dataset due to unrepresentative data).
  - MD (winter wheat) = 325.4 - 162.3 $\log_{10}$ ASR + 0.08022 ATS
  - MD (potatoes) = 326.4- 196.5 $\log_{10}$ ASR + 0.1127 ATS
- The ALC guidance does not currently give any explicit guidance for calculating the moisture deficit under grass, which is focused on crop adjusted moisture deficits. In effect, the PSMD, is the value that should be used for grass although this is not clear in the ALC guidance.
- Jones (1987) reports on regression equations that could be used to calculate the PSMD from ASR and ATS, which account for 85 and 75%, respectively of the variation in the PSMD. However, full details of the equation in which the ASR values are log transformed, in line with the adjusted MD values is not detailed, even though this increases the variance accounted for. The equations for PSMDS and PSMDM (i.e. based on datasets 1 and 2 above) are:
  - PSMDS = -94.9 – 0.3177 ASR + 0.1539 ATS or
  - PSMDM = -106.5 – 0.2055 ASR + 0.1435 ATS
- It has been suggested that PRG growth is restricted when SMD is >40-50 mm (Garwood and Williams, 1967). Chynoweth *et al*. (2012) reported a linear relationship between maximum PSMD and yield with a loss of 3.2 kg/ha/mm of deficit above 50 mm (the critical deficit) and Martin *et al*. (2003) of 3.7 kg/ha/mm. Similarly, it has been noted that when the SMD is >25-30 mm grass growth rates will reduce and at 50 mm SMD grass growth is severely compromised (Teagasc, 2020). In comparison, the land evaluation model used by Rounsevell *et al* (1996) to calculate land suitability for agriculture defines moist and dry climatic zones by a PSMD threshold of 115 mm (dry climate: PSMD >115 mm; moist climate: PSMD <115 mm).

10.4 Moisture balance

- Droughtiness limits for ALC grades are defined in terms of moisture balance (mm) for wheat and potatoes which are calculated as follows:
  - MB (wheat) = AP (wheat) – MD (wheat)
  - MB (potatoes) = AP (potatoes) – MD (potatoes)
- AP and MD are calculated as detailed above and the grade according to droughtiness allocated according to Table 15 below. To be eligible for Grades 1 to 3b the MB must be equal to or exceed the minimum values for both wheat and potatoes. Where AP-MD is >+50 soils are non-droughty, between 0 and 50, slightly droughty, between 0 and -50 moderately droughty and <-50 very droughty.

Table 15. ALC grade according to droughtiness

Grade	Moisture balance limits (mm)		
	Wheat		***Potato***
1	+30	And	+10
2	+5	And	-10
3a	-20	And	-30
3b	-50	And	-55
4	<-50	Or	<-55

- For grass moisture balance should be calculated as:
  - MB (grass) = AP (grass) - PSMD
- ALC grades 1 and 2 are typically used for arable or horticultural crops. It is suggested that moisture balance limits for grass are not differentiated for all the ALC grades but that limit values for ALC grades 3a/3b and for ALC grade 4 are differentiated.
- In the Scottish Land Classification, four drought classes are differentiated according to moisture balance and the suitability for cereal and potato crops:
  1. Non-droughty: AP-MD = ≥50 mm
  2. Slightly droughty: AP-MD = 0-49 mm
  3. Moderately droughty: AP-MD = 0- -50 mm
  4. Very droughty: AP-MD = ≥-50 mm

11 Conclusions

11.1 Rooting depth and drought tolerance

- Root systems of temperate grassland species can grow to great depths; for example, Canadell *et al*. (1996) found a maximum rooting depth of.2.6 ± 0.2 m for temperate grasslands. However, most roots are found at much shallower depths where concentrations of nitrogen, phosphorus and potassium tend to be highest (Jobbágy and Jackson, 2001). In general, temperate grasslands allocate about 40% of their roots to the top 10 cm of the soil profile, and on average 83% occur in the top 30 cm (Jackson *et al*., 1996). This may compromise both their long-term persistency and yield potential following onset of drought conditions (Humphreys *et al*. 2014).
- To obtain maximum above-ground production, large root systems are often not required if water and nutrients are continuously available. When this condition is not met, however, larger root systems may reduce the impact of variations in nutrient and water supply (Noordwijk and Willigen, 1987). Some authors have shown that deep rooted species have increased drought resistance (Skinner *et al*., 2004), reflecting their ability to acquire water from deeper soil layers. In contrast, other authors have suggested that soil water in deeper soil layers might not facilitate drought resistance of deep-rooted species because grassland species under drought do not necessarily shift take up water from deeper soil layers (Hoekstra *et al*. 2014; Prechsl *et al*. 2015). Also, shifting resource uptake to accessing water from deeper layers comes with a trade-off between water and nutrient availability. Generally, while more water is available in deeper soil layers nutrient concentration decreases considerably with increasing soil depth (Dolan *et al*. 2006), especially in fertilised agricultural systems. The benefit of accessing water from deeper soil layers may thus be counteracted by lower nutrient availability. In support of this theory experiments by results reported by Hoekstra *et al.* (2015) and Hofer (2016), suggest that although deep rooting might contribute to drought resistance, the effect could be small and might become important only under extreme drought conditions.

11.2 Crop adjusted water capacity for grass.

- There is currently no guidance in the ALC for calculating crop adjusted water capacity for grass. Thomasson (1979) suggests that the soil water available to permanent grass should be calculated to 100 cm considering the total available water (0.05-15 bar) to 70 cm and the easily available water (0.05-2.0 bar) from 70-100 cm. However, the Thomasson (1979) model was designed for permanent pasture and based on data current in 1979 thus it is questionable how appropriate it is for use with modern varieties or ley grass.
- Based on more recent rooting depth data, most grass roots are predominately shallow, extending to ≤30 cm (e.g. 40% are in the top 10 cm and >80% in the top 30 cm), albeit that there is some variation between species. However, a small proportion of the roots of many species will extend to depths greater than 30 cm. This suggests that the Thomasson (1979) model depths may not adequately represent many present day grass varieties. For example, for the ryegrass species, which predominate in many improved pasture, AP grass (mm) could be calculated based on TAv to a depth 15 cm and based on EA to a depth of 1 m, to account for the sparse root system below 15 cm.

11.3 Soil moisture deficit for grass

- The calculation of the soil moisture deficit is a key component of assessing soil droughtiness for ALC. Moisture deficit represents the balance between rainfall and evapotranspiration. For periods when potential evapotranspiration (PE) exceeds rainfall (R) the potential soil moisture deficit (PSMD) can be calculated as PSMD = ∑ (R-PE); R-PE is calculated daily and summed for a defined period.

- Potential deficits under grass are greater than for arable crops which do not attain full ground cover early in the growing season. Hence, for calculating ALC grade, the PSMD is adjusted for two reference crops, winter wheat and main crop potatoes, which are considered representative of a broad range of crops in terms of their susceptibility to drought. Crop adjusted MDs are smaller than PSMD so that during a dry June or July where several crops are growing in the same soil type, soil moisture deficits follow the sequence root crops < cereals < grass. The ALC guidance does not currently give any explicit guidance for calculating the moisture deficit under grass, which is focused on crop adjusted moisture deficits. In effect, the PSMD, is the value that should be used for grass although this is not clear in the ALC guidance.

11.4 ALC moisture balance

- To allocate the ALC grade according to droughtiness a moisture balance is calculated by subtracting the crop adjusted moisture deficit from the crop adjusted available water. This process is repeated to find the moisture balance for both wheat and potatoes. To be eligible for grades 1-3b the moisture balance must equal or exceed the stated minimum values for both wheat and potatoes. However, it is unlikely that these moisture limit balance values are appropriate for grass and new values for grass should be determined.

12 References

Aamlid, T.S., Heide, O.M. and Boelt, B. (2000). Primary and secondary induction requirements for flowering of contrasting European varieties of *Lolium perenne. Annals of Botany*. 1087-1095.

Abberton, M. (2010). *New opportunities for forage species*. DairyCo.

ADAS (2017). Crop requirements report part 1. Report code: CSCP08/01. Welsh Government.

ADAS (2019). Crop requirements report part 2. Report code: CSCP08/01. Welsh Government.

AHDB (2013). *Using Chicory and Plantain in Beef and Sheep Systems*. AHDB Beef & Lamb.

AHDB (2016). *Growing and Feeding Lucerne*. AHDB Beef & Lamb.

AHDB (2018). *Improving pasture for better returns*. Agriculture and Horticulture Development Board.

AHDB (2018a). *Planning grazing strategies for better returns*. Agriculture and Horticulture Development Board.

AHDB (2019). *Grassland reseeding guide*. Agriculture and Horticulture Development Board.

AHDB (2021). *Nutrient management guide (RB209). Section 3. Grass and forage crops.* Agriculture and Horticulture Development Board.

Anderson, N.P., Chastain, T.G., Hart, J.M., Young, W.C., Christensen, N.W. (2014). *Tall Fescue grown for seed. A nutrient management guide for Western Oregon*. Oregon State University Extension Service.

Australian Government (2003). *The biology of Lolium multiflorum Lam. (Italian ryegrass), Lolium perenne L. (perennial ryegrass) and Lolium arundinaceum (Schreb.) Darbys (tall fescue).* Australian Government Department of Health and Ageing. Office of the Gene Technology Regulator.

Baker, B.S. and Jung, G.A. (1968). Effect of environmental conditions on the growth of four perennial grasses. I. Response to controlled temperature. *Agronomy Journal*. 60, 155-158.

Barenbrug (undated). *Good grass guide. The simple grassland management guide*. Barenbrug UK Ltd.

Beddows, A.R. (1959). *Dactylis glomerata* L. *The Journal of Ecology*. 47, 223-239.

Beddows, A.R. (1961). Biological flora of the British Isles. *Holcus lanatus* L. *Journal of Ecology*. 49, 421-430.

Bond, W., Davies, G. and Turner, R. (2007a). *The biology and non-chemical control of Common Bent (Agrostis capillaris L.).* HDRA.

Bond, W., Davies, G. and Turner, R. (2007b). *The biology and non-chemical control of Yorkshire Fog (Holcus lanatus L.).* HDRA.

Bond, W., Davies, G. and Turner, R. (2007c). *The biology and non-chemical control of Ribwort Plantain (Plantago lanceolata L.).* HDRA.

Bond, W.J., Woodward, F.I. and Midgley, G.F. (2005). The global distribution of ecosystems in a world without fire. *New Phytologist*. 165, 525-538.

Bond, W.J. and Keeley, J.E. (2005). Fire as a global herbivore: the ecology and evolution of flammable ecosystems. *Trends in Ecology and Evolution*. 20, 387-394.

Bothe, A., Westermeier, P., Wosnitza, A., Willner, E., Schum, A., Dehmer, K.J. and Harmann, S. (2018). Drought tolerance in perennial ryegrass (*Lolium perenne* L.) as assessed by two contrasting phenotyping systems. *Journal of Agronomy and Crop Science*. 204, 375-389.

British Grassland Society (2020). *Recommended grass and clover lists for England and Wales*. British Society of Plant Breeders, AHDB and HCC.

BSH, IBERS (undated). *Clover management guide. Increased grazing and cutting potential from cattle and sheep leys.* British Seed Houses and Institute of Biological, Environmental and Rural Sciences.

Bush, T., St John, L., Stannard, M. and Jensen, K.B. (2006). *Orchardgrass. Dactylis glomerata L*. United States Department of Agriculture Natural Resources Conservation Service.

Buttler, A., Mariotte, P., Meisser, M., Guillaume, T., Signarbieux, C., Vitra, A., Preux, S., Mercier, G., Quezada, J., Bragazza, L. and Gavazov, K. (2019). Drought-induced decline of productivity in the dominant grassland species *Lolium perenne* L. depends on soil type and prevailing climatic conditions. *Soil Biology and Biochemistry.* 132, 47-57.

Campbell, B.D., Mitchell, N.D. and Field, R.R.O. (1999). Climate profiles of temperate C3 and subtropical C4 species in New Zealand pastures. *New Zealand Journal of Agricultural Research*. 42. 223-233.

Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E. and Schulze, E.D. (1996). Maximum rooting depth of vegetation types at the global scale. *Oecologia*. 108, 583-595.

Caradus, J.R. (1991). Genetical and environmental effects on white clover root growth and morphology. *Proceedings of the Agronomy Society of New Zealand*. 21, 55-60.

Carbonero, C.H. (2011). *Sainfoin (Onobrychis viciifolia), a forage legume with great potential for sustainable agriculture, an insight on its morphological, agronomical, cytological and genetic characterisation*. A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Life Sciences.

Cavers, P.B., Bassett, I.J. and Crompton, C.W. (1980). The biology of Canadian weeds. 47. *Plantago lanceolata* L. *Canadian Journal of Plant Science.* 60, 1269-1282.

Charlton, J.F.L., Hampton, J.G. and Scott, D.J. (1986). Temperature effects on germination of New Zealand herbage grasses. *Proceedings of the New Zealand Grassland Association*. 47, 165-172.

Charlton, J.F. L. and Stewart, A.V. (2000). Timothy – the plant and it's use on New Zealand Farms. *Proceedings of the New Zealand Grassland Association*. 62, 147-153.

Chou, W.W., Silver, W.L., Jackson, R.D., Thompson, A.W. and Allen-Diaz, B. (2008). The sensitivity of annual grassland carbon cycling to the quantity and timing of rainfall. *Global Change Biology*. 14, 1382-1394.

Chynoweth, R.J., Rolston, M.P. and McCloy, B.L. (2012). Irrigation management of perennial ryegrass (*Lolium perenne*) seed crops. *Agronomy New Zealand*. 42, 77-85.

Ciais, Ph., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, Chr, Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T. and Valentini, R. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*. 437, 529-533.

Clapham, A.R., Tutin, T.G. and Moore, D.M. (1987). *Flora of the British Isles*. 3rd edition, Cambridge University Press, Cambridge, UK.

Collins, R., Marshall, A.H., Ribaimount, F., Michaelson-Yeates T.P.T., Williams T.A., Olyott P. and Abberton M.T. (2006). *Developing the role of Lotus species in UK grasslands*. In: Lloveras, J., González-Rodríguez, A., Vázquez-Yáñez, O., Piñeiro, J., Santamaría, O., Olea, M. and Poblaciones, M.J. (Eds.). Sustainable Grassland Productivity. Proceedings of the 21st General Meeting of the European Grassland Federation Badajoz, Spain 3-6 April 2006.

Conaghan, P. and Clavin, D. (2017). *Red cover – agronomy and management*. Teagasc.

Cougnon, M., Deru, J., Eekeren, N., van., Baert, J. and Reheul, D. (2013). *Root depth and biomass of tall fescue vs. perennial ryegrass*. In: Helgadóttir, A. and Hopkins, A. (Eds.) The role of grasslands in a green future. Threats and perspectives in Less Favoured Areas. Grassland Science in Europe. Volume 18.

Cowan, J.R. (1956). Tall fescue. *Advances in Agronomy* 8, 283-320.

Craine, J.M., Ocheltree, T.W., Nippert, J.B., Towne, E.G., Skibbe. A.M., Kembel. S.W. and Fargione. J.E. (2013). Global diversity of drought tolerance and grassland climate-change resilience. *Nature Climate Change*. 3, 63-67.

Crush, J.R., Nichols, S.N. and Ouyang, L. (2010). Adventitious root mass distribution in progeny of four perennial ryegrass (*Lolium perenne* L.) groups selected for root shape. *New Zealand Journal of Agricultural Research*. 53, 193-200.

Daepp, M., Nosberger, J. and Luscher, A. (2001). Nitrogen fertilization and developmental stage alter the response of *Lolium perenne* to elevated CO_2. *New Phytologist*. 150, 347-358.

DAFF (2013). *Chicory (Chicorium intybus)*. Production Guidelines. Department Agriculture, Forestry and Fisheries, South Africa.

Deléglise, C., Meisser, M., Spiegelberger, T., Mosimann, E., Jeangros, B. and Buttler, A. (2015). Drought-induced shifts in plants traits, yields and nutritive value under realistic grazing and mowing managements in a mountain grassland. *Agriculture, Ecosystems & Environment*. 213, 94-104.

Deryng, D., Elliott, J., Folberth, C., Muller, C., Pugh, T.A.M., Boote, K.J., Conway, D., Ruane, A.C., Gerten, D., Jones, J.W., Khabarov, N., Olin, S., Schapho, S., Schmid, E., Yang, H. and Rosenzweig, C. (2016). Regional disparities in the beneficial effects of rising CO_2 concentrations on crop water productivity. *Nature Climate Change*. 6, 786-790.

Didiano, T.J., Johnson, M.T.J. and Duval, T.P. (2016). Disentangling the effects of precipitation amount and frequency on the performance of 14 grassland species. *PLoS One* 11.

Dolan, M.S., Clapp, C.E., Allmaras, R.R., Baker, J.M. and Molina, J.A.E. (2006). Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. *Soil & Tillage Research*, 89, 221-231.

Döring, T. and Howlett, S. (2013). *Manifold green manures – Part I: Sainfoin and Birdsfoot Trefoil*. The Organic Grower - No 22 spring 2013.

Dunbabin, V., Diggle, A. and Rengel, Z. (2003). Is there an optimal root architecture for nitrate capture in leaching environments? *Plant, Cell and Environment*. 26, 835-844.

Eekeren van, N., Bos, M., Wit de, J., Keidel, H. and Bloem, J. (2010). Effect of individual grass species and grass species mixtures on soil quality as related to root biomass and grass yield. *Applied Soil Ecology.* 45, 275-283.

Eissenstat, D.M. (1992). Costs and benefits of constructing roots of small diameter. *Journal of Plant Nutrition*. 15, 763-782.

Esser, L.L. (1993). *Phleum pratense*. Fire Effects Information System. Fort Collins, CO, USA: USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory

Evans, C. and McConnell, D.A. (2015). *Lucerne as alternative protein source in southwest England: a demo farm perspective*. In: van de Pol-van Dasselaar, A., Aarts, H.F.M., De Vliegher, A., Elgersma, A., Reheul, D., Reijneveld, J.A., Verloop, J., Hopkins, A. eds., (2015). Grassland and forages in high output dairy farming systems. Proceedings of the 18th Symposium of the European Grassland Federation Wageningen, the Netherlands 15-17 June 2015, 407-409.

Fan, Y., Miguez-Macho, G., Jobbágy, E.G., Jackson, R.B. and Otero-Casal, C. (2017). Hydrologic regulation of plant rooting depth. *PNAS*, 114, 10572-10577.

Fiil, A., Jensen, L. B., Fjellheim, S., Lubbersted, T., and Andersen, J. R. (2011). Variation in the vernalization response of a geographically diverse collection of timothy accessions. *Crop Science*. 51, 2689-2697.

Finn, J.A., Kirwan, L., Connolly, J., Sebastià, M.T. Helgadottir, A., Baadshaug, O.H., Bélanger, G., Black, A., Brophy, C., Collins, R.P., Cop, J., Dalmannsdóttir, S., Delgado, I., Elgersma, A., Fothergill, M., Frankow-Lindberg, B.E., Ghesquiere, A., Golinska, B., Golinski, P., Grieu, P., Gustavsson, A-M., Höglind, M., Huguenin-Elie, O., Jørgensen, M., Kadziuliene, Z., Kurki, P., Llurba, R., Lunnan, T., Porqueddu, C., Suter, M., Thumm, U. and Lüscher, A. (2013). Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: a 3-year continental-scale field experiment. *Journal of Applied Ecology*. 50, 365-378.

Fort, F., Jouany, C. and Cruz, P. (2013). Root and leaf functional trait relations in *Poaceae* species: implications of differing resource acquisition strategies. *Journal of Plant Ecology*. 6, 211-219.

Fuller, R.M. (1987). The changing extent and conservation interest of lowland grasslands in England and Wales: a review of grassland surveys 1930–1984. *Biological Conservation*. 40, 281-300.

Garwood, E.A. and Sinclair, J. (1979). Use of water by six grass species 2. Root distribution and use of soil water. *The Journal of Agricultural Science*. 93, 25-35.

Garwood, E.A. and Williams, T. (1967). Soil water use and growth of a grass sward. *The Journal of Agricultural Science.* 68, 281-289.

Ghesquière, M., Humphreys, M. W. and Zwierzykowski, Z. (2010). *Festulolium*. In: Boller, B., Posselt, U.K. and Vernonesi, F. (Eds). Fodder crops and amenity grasses. 288-311. Springer.

Grieu, P., Lucero, D.W., Ardiani. R. and Ehleringer, J.R. (2001). The mean depth of soil water uptake by two temperate grassland species over time subjected to mild soil water deficit and competitive association. *Plant and Soil*. 230, 197-209.

Hall, M.H. (1993). *White clover, Agronomy Facts 22*. Penn State Extension. Pennsylvania State University.

Hannaway, D., Fransen, S., Cropper, J., Teel, M., Chaney, M., Griggs, T., Halse, R., Hart, J., Cheeke, P., Hansen, D., Klinger, R. and Lane, W. (1999). *Perennial ryegrass (Lolium perenne L.).* Oregon State University. PNW 503.

Hill, R. (2017). *Growing Sainfoin*. Cotswold Seeds Ltd.

Ho M.D., Rosas J.C., Brown K.M. and Lynch J.P. (2005). Root architectural trade-offs for water and phosphorus acquisition. *Functional Plant Biology.*32, 737-748.

Hodge, A. (2004). The plastic plant: Root responses to heterogeneous supplies of nutrients. *New Phytologist.* 162, 9-24.

Hoekstra, N.J., Finn, J.A., Hofer, D. and Lüscher, A. (2014). The effect of drought and interspecific interactions on depth of water uptake in deep and shallow-rooting grassland species as determined by δ^{18}O natural abundance. *Biogeosciences*. 11, 4493-4506.

Hoekstra, N.J., Suter, M., Finn, J.A., Husse, S. and Lüscher, A. (2015). Do belowground vertical niche differences between deep- and shallow-rooted species enhance resource uptake and drought resistance in grassland mixtures? *Plant Soil*. 394, 21-34.

Hofer, D., Suter, M., Haughey, E., Finn, J.A., Hoekstra, N.J. Buchmann, N. and Lüscher, A. (2016). Yield of temperate forage grassland species is either largely resistant or resilient to experimental summer drought. *Journal of Applied Ecology*. 53, 1023-1034.

Hoover, D.L., Knapp, A.K. and Smith, M.D. (2014). Resistance and resilience of a grassland ecosystem to climate extremes. *Ecology*. 95, 2646-2656.

Hume, D.E. and Lucas, R.J. (1987). Effects of winter cutting management on growth and tiller numbers of six grass species. *New Zealand Journal of Experimental Agriculture*. 15, 17-22.

Humphreys, J. and Lawless, A. (2006). *A guide to management of white clover in grassland*. Moorepark Dairy Production Research Centre. Series No. 3. Teagasc.

Humphreys, M.W., O'Donovan, S.A., Farrell, M.S., Gay, A.P. and Kingston-Smith, A.H. (2014). The potential of novel *Festulolium* (2n = 4x = 28) hybrids as productive, nutrient-use-efficient fodder for ruminants. *Food and Energy Security*. 3, 98-110.

IGER (undated). *How grass grows*. Institute of Grassland and Environmental Research, Okehampton.

IGER (2003). *Influence of climate change on the sustainability of grassland systems in England and Wales* (CTE9907) - CC0359. Institute of Grassland and Environmental Research, Okehampton.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E. and Schulze, E.D. (1996). A global analysis of root distributions for terrestrial biomes. *Oecologia*. 108, 389-411.

Jacques, W.A. (1962). *Yorkshire Fog as a pasture grass.* New Zealand Grassland Association.

Jobbágy, E.G. and Jackson, R.B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*. 10, 423-436.

Jokela, V., Trevaskis, B and Seppänen, M.M. (2014). Genetic variation in the flowering and yield formation of timothy (*Phleum pratense* L.) accessions after different photoperiod and vernalization treatments. *Frontiers in Plant Science*. 6:465.

Jones, R.J.A. (1987). *The estimation of moisture deficit for the assessment of soil droughtiness in ALC.*

Jones, R.J.A., Zdruli, P. and Montanarella, L. (2000). *The estimation of drought risk in Europe from soil and climatic data*. In: Vogt, J.V. and Somma, F. (Eds). Drought and drought mitigation in Europe, 133-146.

Kasulyte, D. and Praciak, A. (2015). *Datasheet report for Phleum pratense (timothy grass)*. CABI, UK.

Kirwan, L., Lüscher, A., Sebastiá, M.T., Finn, J.A., Collins, R.P., Porqueddu, C., Helgadottir, A., Baadshaug, O.H., Brophy, C., Coran, C., Dalmannsdóttir, S., Delgado, I., Elgersma, A., Fothergill, M., Frankow-Lindberg, B.E., Golinski, P., Grieu, P., Gustavsson, A.M., Höglind, M., Huguenin-Elie, O., Iliadis, C., Jørgensen, M., Kadziuliene, Z., Karyotis, T., Lunnan, T., Malengier, M., Maltoni, S., Meyer, V., Nyfeler, D., Nykanen-Kurki, P., Parente, J., Smit, H.J., Thumm, U. and Connolly, J. (2007). Evenness drives consistent diversity effects in intensive grassland systems across 28 European sites. *Journal of Ecology*. 95, 530-539.

Lacefield, G. and Ball, D. (2000). *White clover*. Oregon Clover Commission.

Lacefield, G.D., Henning, J.C., Philips, T.D. and Rasnake, M. (2002). *Timothy*. University of Kentucky College of Agriculture Cooperative Extension Service. AGR-84.

Laws, D. and Genever, L. (2013). *Using chicory and plantain in beef and sheep systems*. Better Returns Programme. AHDB Beef & Lamb.

Lemus, R. (2017). *Annual ryegrass performance in Mississippi: long-term yield production.* Mississippi State University Extension.

Lolicato, S. and Rumball, W. (1994). Past and present improvement of cocksfoot (*Dactylis glomerata* L.) in Australia and New Zealand. *New Zealand Journal of Agricultural Research*. 37, 379-390.

Lucanus, R., Mitchell, K.J., Pritchard, G.G. and Calder, D.M. (1960). Factors influencing survival of strains of ryegrass during the summer. *New Zealand Journal of Agricultural Research*. 3, 185-193.

Lüscher, A. Mueller-Harvey, I., Soussana, J.F., Rees, R.M. and Peyraud, J.L. (2014). Potential of legume-based grassland–livestock systems in Europe: a review. *Grass and Forage Science*. 69, 206-228.

Lynch, J.P. (2007). Roots of the second green revolution. *Australian Journal of Botany.* 55, 493-512.

MacLeod, C.J.A., Humphreys, M.W., Whalley, R., Turner, L., Binley, A., Watts, C.W., Skøt, L., Joynes, A., Hawkins, S., King, I.P., O'Donovan, S. and Haygarth, P.M. (2013). A novel grass hybrid to reduce flood generation in temperate regions. *Scientific Reports*. 3:1683.

Maczey, N. (2016). *Datasheet report for Agrostis capillaris* (common bent). CABI, UK

MAFF (1988). *Agricultural Land Classification of England and Wales*. October 1988.

Martin, R.J., Gillespie, R.N. and Maley, S. (2003). *Response of perennial ryegrass (Lolium perenne L.) seed yield to irrigation in a second season*. Report to the Foundation for Arable Research (FAR Code: H0203).

Marshall, A.H., Collins, R.P., Humphreys, M.W. and Scullion, J. (2016). A new emphasis on root traits for perennial grass and legume varieties with environmental and ecological benefits. *Food and Energy Security.* 5, 26-39.

Matthew, C., MacKay, A.D. and Robin, A.H.K. (2016). Do phytomer turnover models of plant morphology describe perennial ryegrass root data from field swards? *Agriculture*, 6, 28.

McConnell, D. and Genever, L. (2015). *Growing and feeding lucerne*. AHDB Dairy.

Mitchell, K.J. (1956). Growth of pasture species under controlled environment. 1. Growth at various levels of constant temperature. *New Zealand Journal of Science and Technology, Section A*. 38, 203-215.

Moorehead, A.J.E. and Piggot, G.J. (2009). The performance of pasture mixes containing 'Ceres Tonic' plantain (*Plantago lanceolata*) in Northland. *Proceedings of the New Zealand Grassland Association*. 71, 195-199.

Mudd, C.H. and Mair, R.B. (1961). Performance of eight seeds mixtures at Great House. 1952–1958 *Experimental Husbandry*. 6, 21-50.

Nadja, H. (2004). *Perennial ryegrass seed production in Western Canada*. Agri-Facts. Practical information for Alberta's Agriculture Industry. Alberta Agriculture, Food and Rural Development.

Nagelmüller, S., Kirchgessner, N., Yates, S., Hiltpold, M. and Walter, A. (2016). Leaf Length Tracker: a novel approach to analyse leaf elongation close to the thermal limit of growth in the field. *Journal of Experimental Botany*, 67, 1897-1906.

Nano, C.E.M. and Clarke, P.J. (2011). How do drought and fire influence the patterns of re-sprouting in Australian deserts? *Plant Ecology*. 212, 2095-2110.

Nelson Brown, R. Percivalle, C., Narkiewicz, S. and DeCuollo, S. (2010). Relative rooting depths of native grasses and amenity grasses with potential for use on roadsides in New England. *HortScience*. 45, 393-400.

Nichols, S.N., Crush, J.R. and Woodfield, D.R. (2007). Effects of inbreeding on nodal root system morphology and architecture of white clover (*Trifolium repens* L.). *Euphytica.* 156, 365-373.

Nichols, S.N., Hofmann, R.W., Williams, W.M. and van Koten, C. (2016). Rooting depth and root depth distribution of *Trifolium repens x T. uniflorum* interspecific hybrids. *Annals of Botany*. 118, 699-710.

Nickerson (2017). *The essential guide to forage crops*.

Nie, Z.N., Miller, S., Moore, G.A., Hackney, B.F., Boschma, S.P., Reed, K.F.M., Mitchell, M., Albertsen, T.O., Clark, S., Craig, A.D., Kearney, G., Li, G.D. and Dear, B.S. (2008). Field evaluation of perennial grasses and herbs in southern Australia. 2. Persistence, root characteristics and summer activity. *Australian Journal of Experimental Agriculture*. 48, 424-435.

Noordwijk van, M. and Willigen de, P. (1987). Agricultural concepts of roots: from morphogenetic to functional equilibrium between root and shoot growth. *Netherlands Journal of Agricultural Science*. 35, 487-496.

Natural Resources Wales. (2016). *State of Natural Resources Report (SoNaRR): Assessment of the Sustainable Management of Natural Resources. Technical Report*. Natural Resources Wales.

Ogle, D.G. and St John, L. (2008). *White Clover Trifolium repens L*. United States Department of Agriculture Natural Resources Conservation Service.

Ogle. D.G., St John, L. and Tilley, D.J. (2011). *Plant guide for Timothy.* Plant Guide. United States Department of Agriculture Natural Resources Conservation Service.

Ortiz, M.M. and Smith, L. (2011). *Sainfoin. Surprising science behind a forgotten forage*. Project Number PITN-GA-2011-289377. Cotswold Seeds Ltd.

Peeters, A. (2004). *Wild and sown grasses. Profiles of a temperate species selection: ecology, biodiversity and use.* Food and Agriculture Organisation of the United Nations.

Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*. 193, 120-145.

Popay, I (2013). *Datasheet report for Lolium perenne (perennial ryegrass)*. CABI, UK.

Prechsl, U.E., Burri, S., Gilgen, A.K., Kahmen, A. and Buchmann, N. (2015). No shift to a deeper water uptake depth in response to summer drought of two lowland and sub-alpine C3-grasslands in Switzerland. *Oecologia*. 177, 97-111.

Qi, A., Holland, R.A., Taylor, G. and Richter, G.M. (2018). Grassland futures in Great Britain - productivity assessment and scenarios for land use change opportunities. *Science of the Total Environment.* 634, 1108-1118*.*

Rapson, G.L. and Wilson, J.B. (1992). Genecology of *Agrostis capillaris* L. (Poaceae) — an invader into New Zealand: 2. Responses to light, soil fertility, and water availability. *New Zealand Journal of Botany.* 30, 13-24.

Red Tractor Assurance (2016). *Crop module: Chicory*. Effective from 1st June 2016-31st May 2017: version 3.2 (Crop Risk Category 1). Assured Food Standards

Rosenfeld, A. and Rayns, F. (Undated). *Sort out your soil. A practical guide to Green Manures*. Cotswold Seeds and Garden Organic.

Rounsevell, M.D.A., Brignall, A.P. and Siddons, P. A. (1996). Potential climate change effects on the distribution of agricultural grassland in England and Wales. *Soil Use and Management*. 12, 44-51.

Rudi, H., Sandve, S.R., Opseth, L.M., Larsen, A. and Rognli, O.A. (2010). Identification of candidate genes important for frost tolerance in *Festuca pratensis* Huds. by transcriptional profiling. *Plant Science*. 180, 78-85.

Rumball, W., Keogh, R.G., Lane, G.E., Miller, J.E. and Claydon, R.B. (1997). 'Grassland Lancelot' plantain (*Plantago lanceolata* L.). *New Zealand Journal of Agricultural Research*. 40, 373-377.

SARE (2012). *Managing cover crops profitably*. Third Edition. Sustainable Agriculture Research & Education.

Schenk, H.J. (2008). The Shallowest Possible Water extraction profile: A Null Model for Global Root Distributions. *Vadose Zone Journal*, 7, 1119-1124.

Schenk, H.J. and Jackson, R.B. (2002). Rooting depths, lateral root spreads and below-ground/ above-ground allometries of plants in water-limited ecosystems. *Journal of Ecology*. 90, 480-494.

Seppänen, M., Pakarinen, K., Jokela, V., Andersen, J. R., Fiil, A., Santanen, A. and Virkajärvi, P. (2010). Vernalization response of *Phleum pratense* and its relationships to stem lignification and floral transition. *Annals of Botany*, 106, 697-707.

Skinner, R.H. and Comas, L.H. (2010). Root distribution of temperate forage species subjected to water and nitrogen stress. *Crop Science*. 50, 2178-2185.

Skinner, R.H., Hanson, J.D. and Benjamin, J.G. (1998). Root distribution following spatial separation of water and nitrogen supply in furrow irrigated corn. *Plant and Soil*. 199, 187-194

Skinner, R.H. (2008). Yield, root growth, and soil water content in drought stressed pasture mixtures containing chicory. *Crop Science*. 48, 380-388.

Skinner, R.H., Gustine, D.L. and Sanderson, M.A. (2004). Growth, water relations, and nutritive value of pasture species mixtures under moisture stress. *Crop Science*. 44, 1361-1369.

Smith, J. and Valenzuela, H. (2002). *White clover*. Sustainable Agriculture Cover Crops. Cooperative Extension Service. College of Tropical Agriculture and Human Resources.

SMG (2015). *Grass & forage crops handbook 2015/16*. Sinclair McGill. Limagrain UK Ltd.

Stewart, A.V. (1996). Plantain (*Plantago lanceolata*) – a potential pasture species. *Proceedings of the New Zealand Grassland Association*. 58, 77-86

St. Clair, S.B., Sudderth, E.A., Fischer, M.L., Torn, M.S., Stuart, S.A., Salve, R., Eggetts, D.L. and Ackerly, D.D. (2009). Soil drying and nitrogen availability modulate carbon and water exchange over a range of annual precipitation totals and grassland vegetation types. *Global Change Biology*. 15, 3018-3030.

St John, L. and Ogle, D. (2008). *Red clover*. *Trifolium pratense L.* United States Department of Agriculture Natural Resources Conservation Service.

Teagasc (2020). *Grass supply must be monitored*. Teagasc Advisory Newsletter June 2020.

Thébault, A., Mariotte, P., Lortie, C.J. and MacDougall, A.S. (2014). Land management trumps the effects of climate change and elevated CO_2 on grassland functioning. *Journal of Ecology*. 102, 896–904.

Thomas, B., Collier, R. and Green, L. (2010). *Climate change impacts and adaptation – a risk-based approach*. Annex 1. Impact of climate change on grassland. Defra Project AC0310.

Thomasson, A.J. (1979), *Assessment of soil droughtiness*. In: Jarvis, M.G. and Mackney, D. (Eds) Soil Survey Applications. Technical Monograph No. 13., 43-50.

Thompson, J.D. and Turkington, R. (1988). The biology of Canadian weeds. 82. *Holcus lanatus* L. *Canadian Journal of Plant Science.* 68, 131-147.

Thorogood, D. (2003). *Perennial ryegrass (Lolium perenne L.).* pp. 75-105. Chapter 7. In: Casler, N.D. and Duncan, R.R. (Eds) Turfgrass biology genetics and breeding. Edition 1. John Wiley & Sons.

Troelstra, S.R. and Brouwer, R. (1992). *Mineral nutrient concentrations in the soil and in the plant.* pp. 122-137. In: Kuiper, P.J.C.; Bos, M. (Eds). Ecological Studies Analysis and Synthesis, Vol. 89. Plantago: a multidisciplinary study. Berlin: Springer-Verlag.

Undersander, D., Smith, R.R., Kelling, K., Doll, J., Worf, G., Wedberg, J., Peters, J., Hoffman, P. and Shaver, R. (1990). *Red clover. Establishment, management and utilisation*. University of Wisconsin Extension.

Undersander, D., Greub, L., Leep, R., Beuselinck, P., Wedberg, J., Smith, D., Kelling, K., Doll, J., Cosgrove, D., Grau, C., Peterson, S., Wipfli, M. and English, J. (1993). *Birdsfoot trefoil for grazing and harvested forage*. North Central Region Extension Publication 474.

Undersander, D., Cosgrove, D., Cullen, E., Grau, C., Rice, M.E., Renz, M., Sheaffer, C., Shewmaker, G. and Sulc, M. (2011). *Alfalfa Management Guide*. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Beguería, S., Trigo, R., López-Moreno, J., AzorínMolina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E. and Sanchez-Lorenzo, A. (2012). Response of vegetation to drought timescales across global land biomes *Proceedings of the National Academy of Sciences of the United States of America*. 110, 52-57.

Vleugels, T., Amdahl, H., Roldán-Ruiz, I. and Cnops, G. (2019). Factors underlying seed yield in red clover: review of current knowledge and perspectives. *Agronomy*. 9, 829.

Vogel, A., Scherer-Lorenzen, M. and Weigelt, A. (2012). Grassland resistance and resilience after drought depends on management intensity and species richness. *PLoS ONE*. 7, e36992.

Watling, G. (2016) *Datasheet report for Festuca arundinacea (tall fescue).* CABI UK.

Watt, T.A. (1978). The biology of *Holcus lanatus L*. (Yorkshire fog) and its significance in grassland. *Herbage Abstracts*. 48, 195-204

Weber, E. (2003). *Invasive plant species of the world. A reference guide to environmental weeds*. CABI Publishing, Cambridge, UK.

Wedderburn, M.E., Crush, J.R., Pengelly, W.J. and Walcroft, J.L. (2010). Root growth patterns of perennial ryegrasses under well-watered and drought conditions, *New Zealand Journal of Agricultural Research*. 53, 377-388.

Welsh Government (2019). *Farming facts and figures, Wales 2019*. Statistics for Wales.

Wilkins, R. J., Bertilsson, J., Doyle, C.J., Noussiainen, J., Paul, C. and Syriala-Qvist, L. (2002). *Introduction to the LEGSIL project*. In: Wilkins, R.J. and Paul, C. (Eds). Legume Silages for Animal Production – LEGSIL. Landbauforschung Völkenrode, FAL Agricultural Research, Sonderheft 234. Braunschweig, Germany.

Zwicke, M., Picon-Cochard, C., Morvan-Bertrand, A., Prudhomme, M-P. and Volaire, F. (2015). What functional strategies drive drought survival and recovery of perennial species from upland grassland? *Annals of Botany*. 116, 1001-1015.