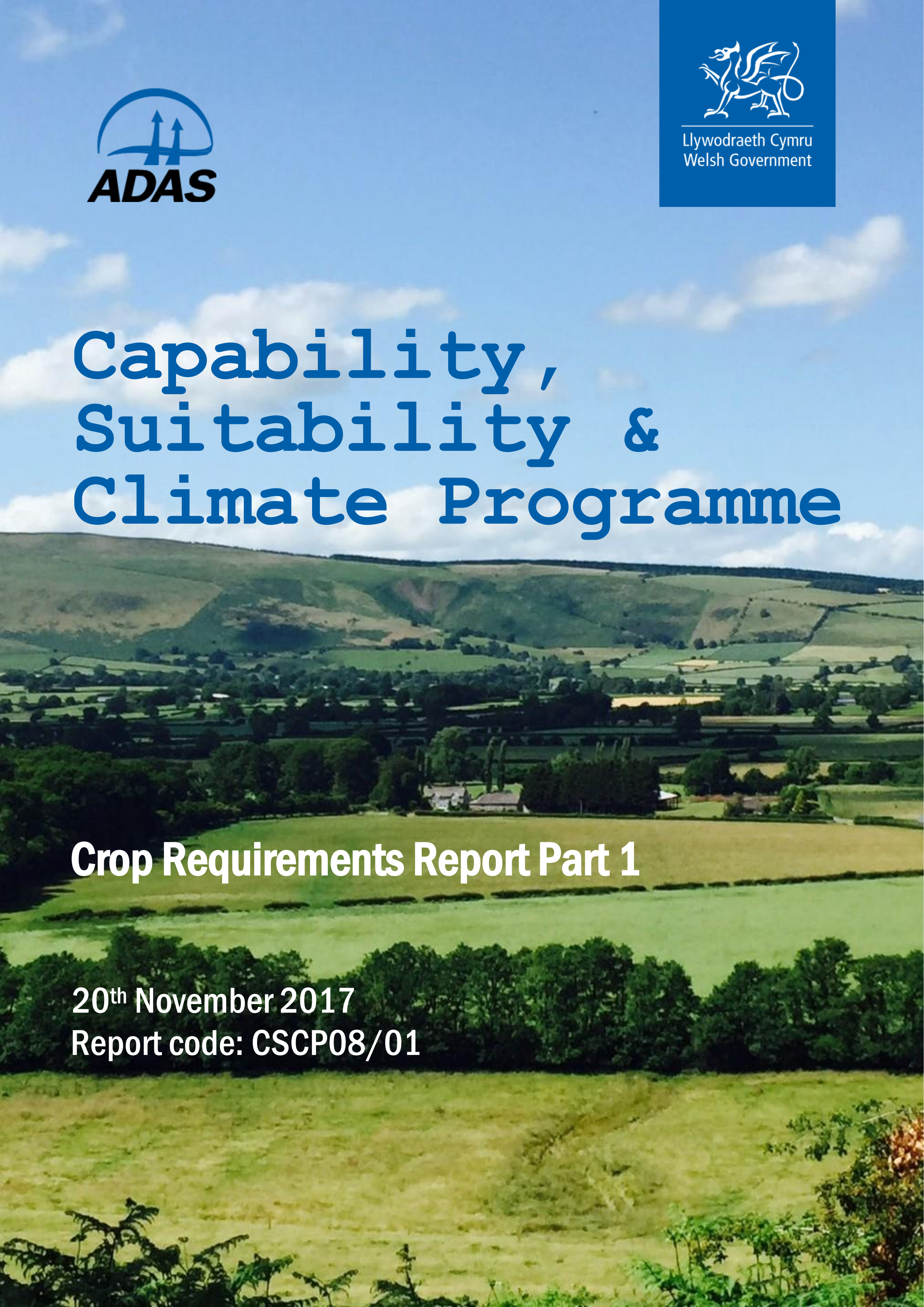

Llywodraeth Cymru
Welsh Government

Capability, Suitability & Climate Programme

Crop Requirements Report Part 1

20th November 2017
Report code: CSCP08/01

Crop Requirements

Submitted to:
James Cooke
Welsh Government
Department for Environment and Rural Affairs
Spa Road East
Llandrindod Wells
Powys, LD1 5HA

20 November 2017

Contents

Introduction

The climate of Wales is cool temperate, with cool summers and mild winters. Local climate is strongly influenced by topography, aspect and altitudinal gradients in temperature and rainfall that lead to microclimatic variations. Of the total land area of Wales, 60% is more than 150 m above sea level, and 27% is more than 300 m above sea level (Russell *et al*., 2011), which will limit the potential for agricultural crop production. The optimal zones for agricultural production are related to both climatic and soil conditions. High altitudes, acid soils and impeded drainage have prevented arable cropping and grassland intensification over large parts of Wales. As a result, around 80% of the agricultural land in Wales has been designated under the Less Favoured Area (LFA) Directive (EU Directive 75/268/EEC of 28 April 1975). LFA land is characterised by climatic limitations and shallow, stony and/or peaty soils with limited agricultural potential and below average economic returns (Armstrong, 2016).

Welsh agriculture is dominated by grassland (permanent pasture and rough grazing), which accounts for more than 70% (1.3 million ha) of the utilised area. In comparison, cropping accounts for 13% (0.25 million ha) of the area, 10% is common rough grazing (0.18 million ha) and the remaining 5% woodland or other land on agricultural holdings (Welsh Government, 2016). Of the 247,000 ha of cropped land in 2015, 64% (*c*.158,000 ha) was grass under 5 years old and 36% (89,000) was tillage land (arable and horticulture). Almost half of the tillage land (42,000 ha) was in Pembrokeshire and South Wales; more than 50% of the area of tillage crops was cereals, in particular wheat and barley (Figure 1). Of the total tillage land, 37,500 ha (42%) was designated as LFA (Welsh Government, 2015).

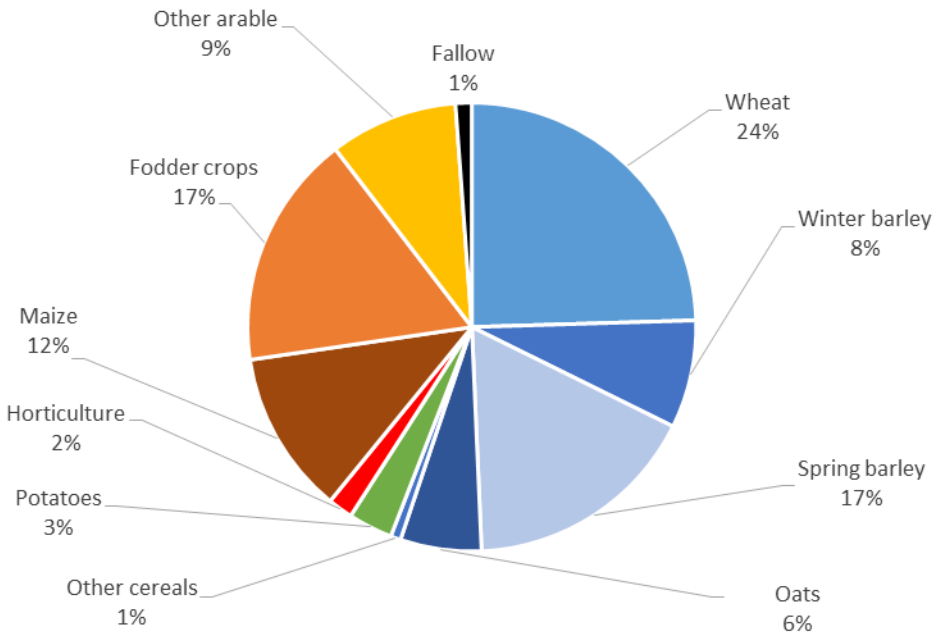

Figure 1. Tillage cropping in Wales (% of area in 2015)

Given that in 2015 more than 60% of cropped land was in 'temporary' grass, there may be scope for increasing the area of arable and horticulture crops in Wales if the change in farming system was economically viable. This report considers 21 crops (5 arable, 14 horticultural, 1 ornamental and grapes) that could be grown in suitable areas of Wales in terms of climatic and site limitations, soil depth, soil stone content, soil wetness/drainage and soil pH status (Table 1). The report covers both land capability (i.e. the general assessment of, for example, climatic and soil factors without taking into consideration land use) and suitability (i.e. the fitness for the production of a specific crop). Climatic, site and soil limitations are discussed in Sections 2-4, and the individual crop requirements are given in Section 5. In addition, the Agricultural Land Classification (ALC) groups that would potentially be suitable for each crop is also given. An accompanying Excel spreadsheet of crop requirement parameters has also been produced.

Table 1. List of crops

Number	Crop
	Arable
1	Potatoes
2	Barley
3	Wheat
4	Oilseed rape
5	Maize
	Horticulture
6	Asparagus
7	Cauliflower
8	Squash
9	Courgettes
10	Parsnips
11	Carrots
12	Celeriac
13	Onions
14	Leeks
15	Rhubarb
16	Raspberries
17	Blackberries
18	Currants
19	Salad Crops
	Viticulture
20	Grapes
	Ornamental
21	Daffodils

The environment

Agriculture plays a major role in the management of natural resources and the provision of ecosystem services and biodiversity. In recent times, Government policy has shifted from a focus on food production to one where environmental protection is also important. Farmers manage 81% of the total Welsh land area and must sustain the balance between agricultural production and environmental management. This includes over 600,000 ha of environmentally designated areas, which are given to protect biodiversity and/or scientific interest in vulnerable areas. There are three National Parks (Snowdonia, Pembrokeshire Coast and Brecon Beacons), five Areas of Outstanding Natural Beauty (Gower, Wye Valley, Clwydian Range, Ynys Mon and Llyn Peninsula), 69 National Nature Reserves and >1000 Sites of Special Scientific Interest in Wales[1]. Statutory environmental management is required in order to receive the Single Farm Payment (i.e. cross compliance and The Code of Good Agricultural Practice). In addition, farmers also undertake voluntary environmental management under agri-environment schemes.

[1] https://www.nfu-cymru.org.uk/assets/13917

It is essential that any changes to cropping strategies (e.g. from temporary grassland to arable production) will not have an adverse effect on the environment and are fully compliant with any specific requirements in designated areas.

Climatic limitations

Climate has a major and, in places, overriding influence on land quality by controlling both the range of agricultural uses and the cost and level of production. The most fundamental influence of climate is on the potential for plant growth, by determining the energy available for photosynthesis. However, climate also influences soil wetness, soil aeration, the number of field capacity days and the ease of access to land to carry out field operations. In climatic terms, the most limited areas are both the wettest and coldest and conversely the climate is regarded as more favourable as temperature increases and rainfall moderates (MAFF, 1988).

Day length

The photoperiod is the amount of light and darkness in a daily cycle of 24 hours. The annual cycle of variation in photoperiod is consistent from year to year and is thus a more reliable indicator of the time of year than temperature (Jackson, 2008). Plants can be classified according to their photoperiodic response; most commonly their flowering response, although other aspects of their development are affected by day length (Taiz and Zeiger, 1991). The two main photoperiodic categories are short-day plants, in which flowering occurs only on short days or is accelerated by short days, and long-day plants, in which flowering occurs only on long days or is accelerated by long days. Temperate plants are frequently long-day types, which helps ensure flowering in the summer months. However, in many plants, known as day-neutral plants, flowering is not regulated by day length. Barley and wheat are both long-day plants whereas in potatoes, short days promote tuberisation and long days inhibit it, however, this response has been bred out of many commercially grown potatoes (Jackson, 2008). Maize is an example of a day-neutral plant; day neutral plants flower after a set time from germination or dormancy breaking.

In a field situation, neither the day length nor the photoperiod can be controlled, but plant performance can be optimised by sowing/planting at the correct time. Where a crop has a known response to day length this has been noted.

Sunshine hours

The topography of Wales combined with the frequency of Atlantic depressions result in significant cloud cover at regular intervals. On average, there is 1454 sunshine hours annually in Wales (10 year average 2007-2016); the sunniest area is the south west coast of Pembrokeshire with >1700 sunshine hours, whereas the mountainous regions have <1200 hours (Met Office, 2016). May and June typically have the most sunshine (188 hours) and December the least (45 hours) (Met Office, 2017). The key controlling factors are cloud cover and day length.

Within the UK, changes in latitude (50 to 60°N) can affect the daily solar radiation receipt, particularly during the winter. In the summer latitude has less of an effect on potential daily radiation because lower solar intensity in the north is compensated by longer day length. Cloud cover can reduce the amount of solar radiation by 50% (light cover) to 75% (thick cover). In Wales, there is little latitudinal variation in the longest and shortest days due to the small difference in latitude across the country (*c*.51-53°N).

Plant chlorophyll absorbs radiation from the sun in the visible light range 400-700 nm (photosynthetically active radiation-PAR) to drive photosynthesis. The rate of photosynthesis is controlled by the level of carbon dioxide, temperature and light intensity. For most temperate crops, carbon dioxide is the most common limiting factor as light saturation is achieved at intensities lower than the light intensity experienced on most UK summer days (Fuller and Jellings, 1988).

Growing period

For the Agricultural Land Classification (ALC) system the period January to June is considered the critical growth period for most crops. Accumulated temperature (AT0) is a measure of the relative warmth of a locality and is the excess of daily air temperature above 0°C (for the ALC system). For the ALC, AT0 is calculated using the equation:

AT0 (day degrees Celsius) = 1708 – 1.14A – 0.023E – 0.044N

A: Altitude above mean sea level (metres). E: is National Grid easting to 100 m and N is National Grid northing to 100 m.

The AT0 ranges from *c*.600-800°C where the altitude is highest (*c.* 600-800 m) to >1200°C at altitudes of ≤200 m in, for example, Pembrokeshire. The lapse rate for temperature was calculated as 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.

Frost

The average number of days with frost varies widely across Wales. The main controls are distance from the sea and altitude, but the ability for cold air to drain into inland valleys is another important factor (Met Office, 2016). 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. On average there is 46 days with air frost in Wales (2007-2016), with the frostiest months being January (10 days), February (9 days) and December (9 days) (Met Office, 2017). Sites along the west coast of Wales typically have fewer than 25 days of air frost each year and inland the number ranges from 40 to 80 days, generally increasing with distance from the coast. The number of days per month with a frost for four locations, with a range of altitudes (10-360 m above mean sea level-amsl) are shown in Figure 2 below. For the sites at a higher altitude the number of days with a frost in January, February and December (the frostiest months) is almost twice that of the lower sites. At the higher sites, the risk of later spring frosts (May) and earlier autumn frosts (September and October) is also increased. The number of days of air frost in winter (December-February), spring (March-May), summer (June-August) and autumn (September-November) is shown in Figure 3. Ground frost occurs on average on about 40 days each year on coasts and over 110 days well inland, with a similar distribution to air frost. Figure 4, shows the number of days of ground frost in Wales in autumn, winter, spring and summer.

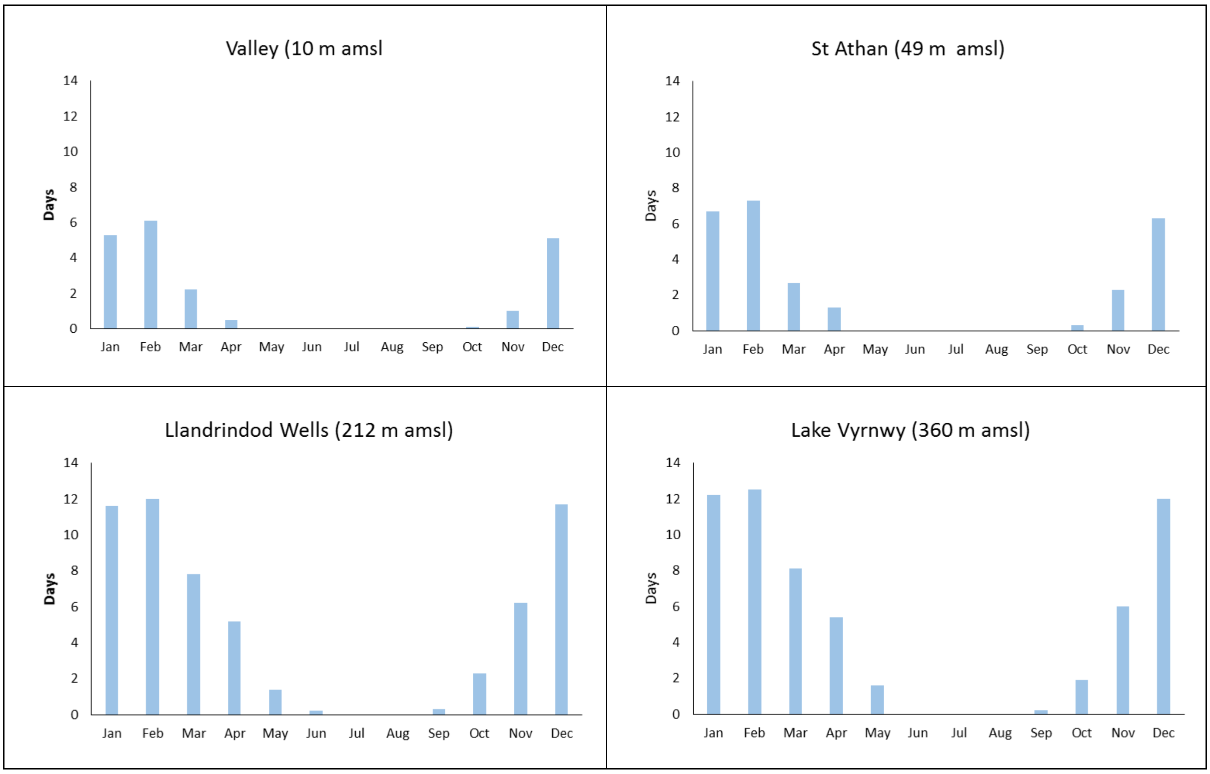

Figure 2. Annual distribution of air frost (days) at four locations with different altitudes: Valley (10 m above mean sea level-amsl – coastal), St Athan (49 m amsl), Llandrindod Well (212 m amsl) and Lake Vyrnwy (360 m amsl).

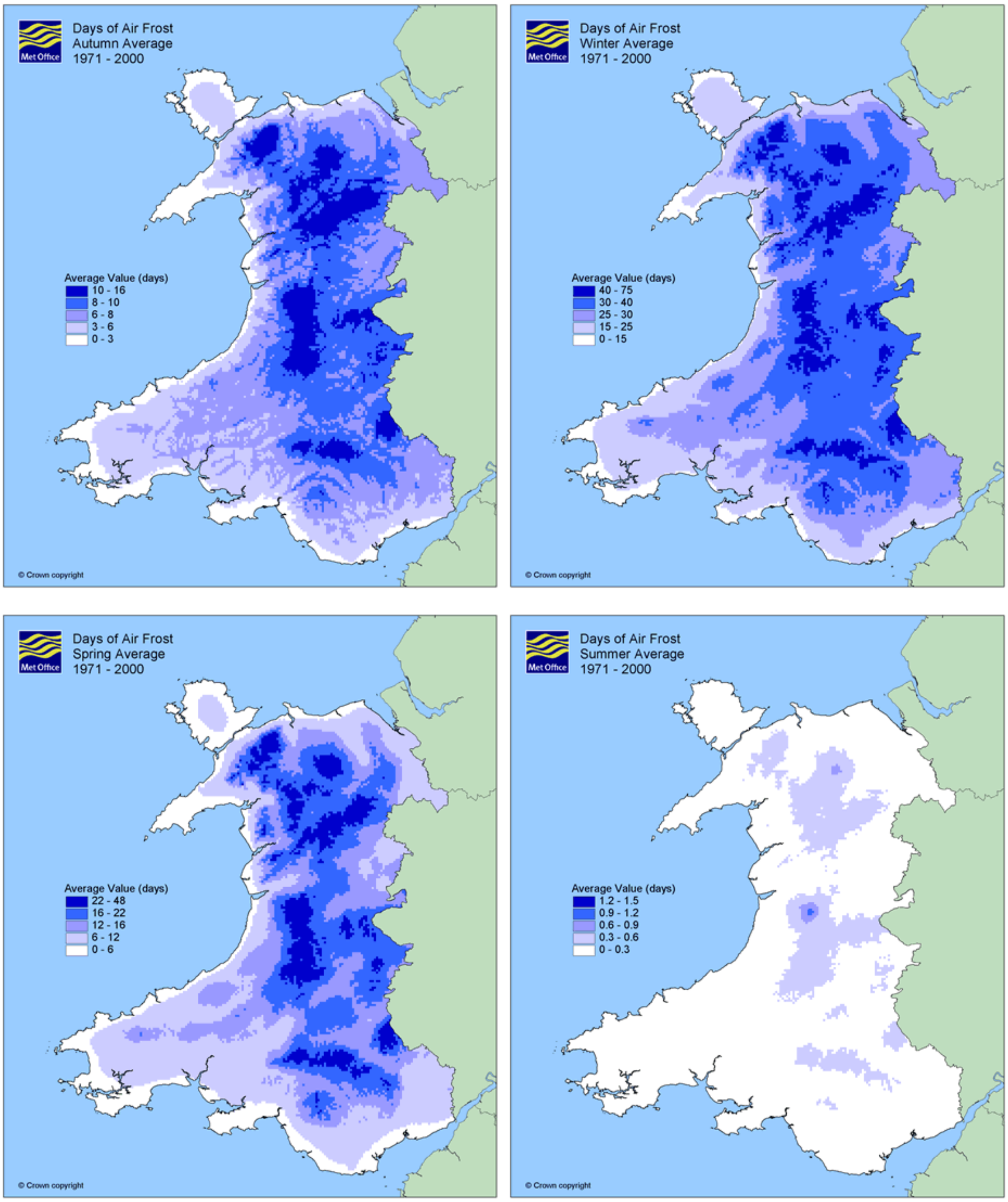

Figure 3. Days of air frost in autumn, winter, spring and summer for Wales between 1971 and 2000.

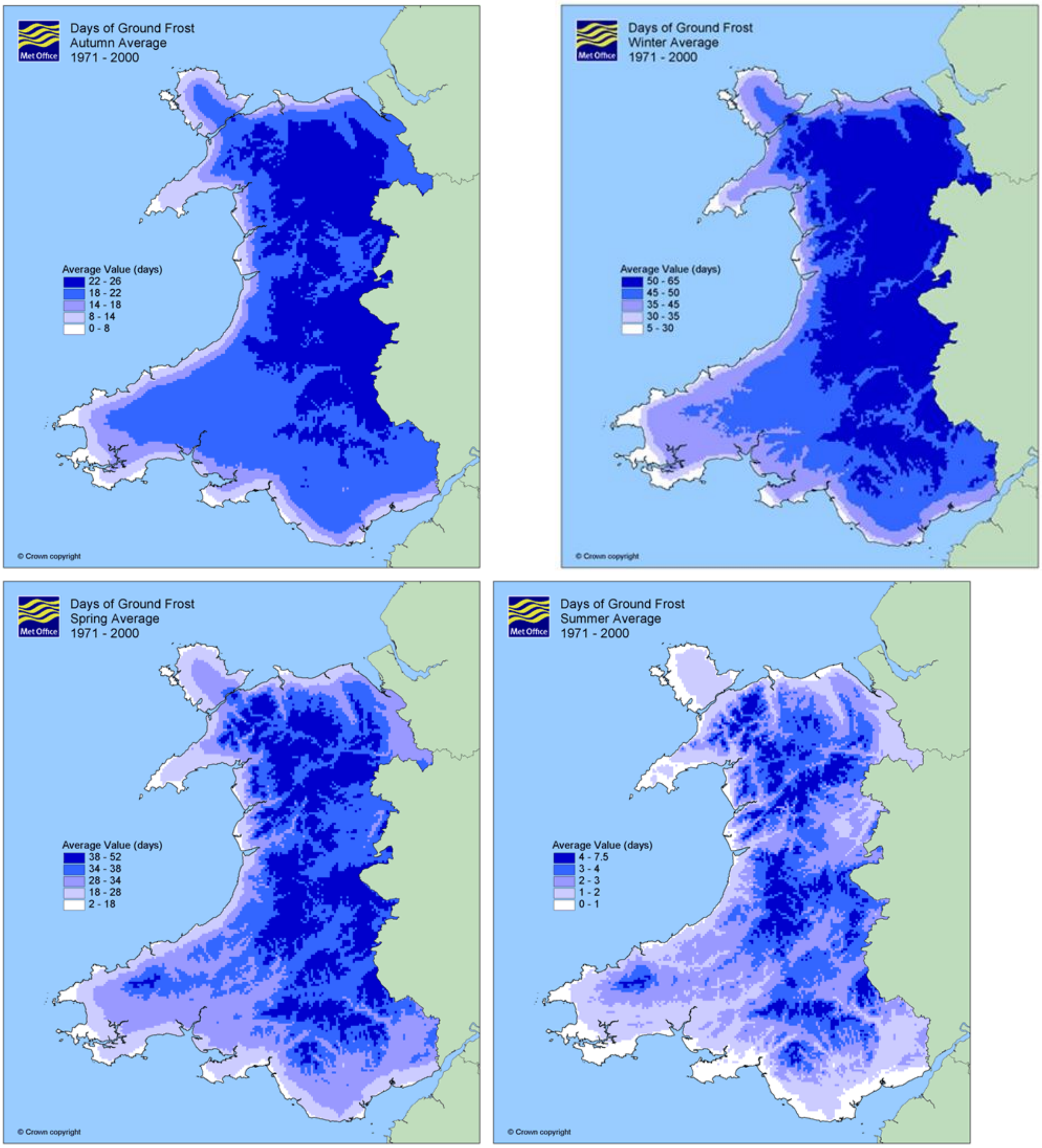

Figure 4. Days of ground frost in autumn, winter, spring and summer for Wales between 1971 and 2000.

Low temperature injury can occur in all plants. Frost damage occurs when ice forms inside the plant tissue and injures the plant cells (Snyder and de Melo-Abreu, 2005). Frost damage can be direct when ice crystals form inside the cell (i.e. intracellular) or indirect when freezing occurs inside the plant but outside the cells (i.e. extracellular). Plants resist low temperatures by 'hardening' which involves mechanisms of avoidance and tolerance of freezing. For example, the accumulation of sugars or sugar alcohols lowers the freezing temperature of plant tissues and cells may harden by increasing the proportion of unsaturated fatty acid. Wang (2016) grouped fruit and vegetable crops into three freeze susceptibility categories from most susceptible to least susceptible (Table 2) for crop storage. However, for crops that overwinter, including perennial fruit crops and certain vegetable crops such as cauliflower, the exposure to a sufficient amount of chilling is essential for subsequent development. For apple, periods of low temperatures (<12°C) are needed to induce dormancy in early winter and also a further period of low temperature (e.g. 1000 h at 6-9°C) is required for dormancy release (Heide and Prestrud, 2005). Spring flowering bulbs such as daffodil and crocus also require a period of winter chilling.

Table 2. Susceptibility of selected crops to freezing injury during crop storage

Most susceptible	**Moderately susceptible**	**Least susceptible**
Asparagus	Apples	Brussel sprouts
Berries	Carrots	Cabbage
Lettuce	Cauliflower	Kale
Potatoes	Grapes	Parsnips
Squash (summer)	Onions	
	Squash (winter)	

Field experiments on critical damage temperatures for fresh fruits and vegetable crops are somewhat limited, but the highest freezing temperatures (i.e. the temperature closest to 0°C at which frost damage occurs) from studies on fruit and vegetable storage are provided in Table 3 (Snyder and de Melo-Abreu, 2005). Although the critical damage temperatures (in Table 3) might be slightly higher than the air temperatures at which damage is expected under field conditions, the information can be useful as a guide. In addition, a range of critical damage temperatures for crops at germination, flowering and fruiting are given in Table 4 (Snyder and de Melo-Abreu, 2005).

Table 3. Highest freezing temperature (i.e. the temperature closest to 0°C) at which damage occurs for selected crops in storage

Crop	**Temperature (°C)**
Asparagus	-0.6
Blackberry	-0.8
Raspberry	-0.9
Strawberry	-0.8
Carrots	-1.4
Cauliflower	-0.8
Celeriac	-0.9
Currants	-1.0
Grape	-2.7 (fruit). -2.0 (stem)
Leek	-0.7
Onions	-0.9
Parsnip	-0.9
Potato	-0.8
Rhubarb	-0.9
Squash	-0.8
Courgette	-0.5

Table 4. A range of critical damage temperatures for selected crops relative to phenological stage.

Crop	Germination	Flowering	Fruiting
Spring wheat	-9, -10	-1, -2	-2, -4
Oats	-8, -9	-1, -2	-2, -4
Barley	-7, -8	-1, -2	-2, -4
Peas	-7, -8	-2, -3	-3, -4
Beans	-5, -6	-2, -3	-3, -4
Carrot	-6, -7		
Cabbage	-5, -7	-2, -3	-6, -9
Maize	-2, -3	-1, -2	-2, -3
Potato	-2, -3	-1, -2	-1, -2

During severe frost events with no snow, the young leaves of grasses and winter cereals seedlings may be damaged, but recovery is possible if the tillering node is not affected. However, if the meristem is damaged, winter kill will occur (Snyder and de Melo-Abreu, 2005). In Finland, winter damage accounts for 60% of the annual variation in winter wheat yields (Mukula and Rantanen 1989). Later in the season, during flowering and initial grain fill of cereals, frost damage reduces the number of kernels per spike. For cereal crops, the relative resistance to freezing of cereals is (from most resistant): Rye > Bread wheat > Triticale > Barley > Oats and Durum wheat (Lindén *et al*., 1999). Potatoes may also be damaged by frosts. The lethal temperature for cultivated potato is c. -3°C (Seppänen *et al*. 1998), although the photosynthetic capacity is reduced at higher temperatures.

Grapes and wine grapes are often damaged by spring frosts. Since leaves form first, they are more prone to damage, but flowers and small berries are also susceptible. Full recovery is common for leaf damage, but fruit damage can reduce production. Early autumn frosts increases susceptibility to fungal attack (e.g. botrytis). During winter, dormant buds are very rarely damaged, since they can resist temperatures below -10°C, down to -20 or even -30°C (Leddet and Dereuddre, 1989 cited by Snyder and de Melo-Abreu, 2005). Similarly, blackberries and blueberries are hardy in winter, so frost damage occurs almost exclusively to the flowers and small fruits in the spring.

An estimate of the risk of frost damage to each crop type has been given in Section 5.

Other climatic factors – snow and wind.

The numbers of days with snow falling and snow lying increase with latitude and altitude, with values reflecting topography. Snow is comparatively rare near sea level in Wales, but much more frequent over the hills (Met Office, 2016). The average number of days each year when sleet or snow falls varies from 10 or less in south-western coastal areas to over 30 in Snowdonia. Snow rarely lies on the ground at sea level before December or after March, and the average number of days with snow lying in Wales varies from 5 or less around the coasts to over 20 in Snowdonia.

Snow is generally a good insulator (Bonan 2002) and the insulating capacity depends on the density of the snow, i.e. on the amount of air it contains (Chernov 1985). Thinner and denser snow has lower insulation capacity (Sturm *et al*. 1997) causing higher variability in temperatures below the snow (Rixen *et al*. 2008). Throughout the winter, the snow cover protects soils and vegetation from low temperatures and harsh winds (Jones 1999; Walker *et al*. 1999). In addition, snow melt provides moisture for the growing plant (Torp, 2010).

Winter cereals can be affected by 'snow rot' and Pink Snow Mould. Snow rot is caused by *Sclerotia* infections, however, plants can often compensate for dead tillers so that yield loss is typically low. Pink Snow Mould, may affect winter barley after snow melts in the spring. Plants die-off in patches but good growing conditions in the spring can allow crop recovery. For both diseases, in years with prolonged snow cover the disease can be severe and re-drilling with a spring crop may be necessary[2] [3].

Crop damage by wind may include leaf tearing, stem damage or uprooting. Wheat, oats, barley, maize and oilseed rape crops are particularly susceptible to wind damage by lodging (Gardiner *et al*., 2016). In addition, high wind speeds can blow shallow rooted brassicas over and uproot them. Lodging can take the form of stem lodging due to the bending or breaking of the lower culm internode or root lodging due to failure of root anchorage. The type and location of lodging varies between cereal species, the agronomy applied to the crop, and the growth stage of the plant. At flowering, the most common form of lodging in wheat and barley is root lodging. But there can also be stem lodging in one of the bottom internodes, especially where the supply of nitrogen is high (Berry *et al*., 2000). "Brackling" (failure of middle internodes) is common in barley. Internode buckling or creasing is also common in the lodging of maize, although it almost always occurs within a few centimetres of a node due to a localized concentration of stress (Robertson *et al*., 2015). Stem failure in general tends to become more common as harvest approaches and the stem dries out (Berry *et al*., 2004). In order to reduce damage, suitable species, appropriate cultivation and nutritional management is essential according to local conditions.

Crops that have particular susceptibility to wind damage have been noted in the individual crop sections below.

Temperature

The mean annual temperature at low altitudes in Wales varies from about 9.5°C to 11°C, with the higher values occurring around or near to the coasts. The mean annual temperature decreases by approximately 0.5°C for each 100 m increase in height so that, for example, a location at 400 m would have a mean annual temperature of between 5.5°C and 9°C (Met Office, 2016).

The growth rate of most plants responds to changes in temperature. For most UK crops the base temperature for growth is 0-1°C and the maximum temperature is 35°C. For crops, that originate from warmer climates, such as maize, the base temperature is around 6-8°C. Where the base temperature is lower (e.g. wheat), growth will commence early in the spring (e.g. March or April) whereas for Maize rapid growth will not start until June/July.

Climate change may lead to increases in mean annual temperatures. For many field grown horticultural crops any increase in temperature could be beneficial by increasing the geographic range and harvesting period in Wales. In contrast, for cool season crops, such as cauliflower, temperature increases could reduce yield (Olesen and Grevesen, 1993).

For determinate species such as cereals, oilseed and protein crops the duration to maturity depends on temperature and in many cases day length (Bindi and Howden, 2004). Thus in some cases a temperature increase would shorten the length of the growing period, reducing yields if management was not altered (Porter and Gawith, 1999). Similarly, onions are also determinate species, so warming might reduce the duration of crop growth and hence yield. In comparison, carrots are indeterminate and warming stimulates growth and yield (Wheeler *et al* 1996; Wurr *et al*., 1998 in Bindi and Howden). Also, grape vines require relatively high temperatures (Bindi and Howden, 2004) and an increase in temperature could increase the area of land suitable for cultivation.

The interaction between temperature and yield can be complex. For monocarpic crops such as cereals, increasing temperatures can reduce yield by shortening the time to reach maturity i.e. flowering and seed set (Wheeler *et al*., 1996, Moot *et al*., 1996). Similar effects may be seen with horticultural crops harvested at maturity such as onions (Daymond *et al*., 1997), whereas the acceleration of growth and

[2]https://cereals.ahdb.org.uk/cereal-disease-encyclopedia/diseases/snow-rot-(grey-or-speckled-snow-mould).aspx

[3] https://cereals.ahdb.org.uk/cereal-disease-encyclopedia/diseases/snow-mould-(pink-snow-mould).aspx

development in root or leafy crops is likely to increase yield for a given harvest date (Wheeler *et al*., 1994, Pearson *et al*., 1997).

Crops can suffer from heat stress, for example, heat stress is an important constraint to wheat productivity at different growth stages, especially anthesis and grain filling (Rehman *et al*., 2009). Wardlaw *et al*. (1989) reported 3–4% reductions in yield per ear for every 1°C rise in temperature above a mean of 15°C from anthesis to maturity. And for maize, Lobell *et al*. (2011) reported that each degree day spent above 30°C (up to 150 days after sowing) reduced the final yield by 1% under optimal rain-fed conditions, and by 1.7% under drought conditions. In a global analysis, Lobell and Gourdji (2012) found that an increase in average temperatures over the growing season of major cereals of about 0.75°C between 1980 and 2011 decreased wheat and maize yields by about 5%. Other examples of heat sensitivity are reported in legumes and brassicas. Daily maximum temperatures above 25°C are considered the threshold level for heat stress in cool-season legume crops. Productivity of these food legumes is affected by both high and low temperature stresses (Kaushal *et al*, 2016). High temperatures during crop growth of both cauliflower and broccoli can increase leaf production (Brewster and Sutherland 1993) and this can lead to buttoning when plants produce small curds or heads that are prematurely exposed by the covering leaves (Wien and & Wurr 1997 cited by Defra (2008)).

In practice, heat stress is not typically a problem for UK crop production.

Rainfall

Rainfall in Wales varies widely, with the highest average annual totals being recorded in the central upland spine from Snowdonia to the Brecon Beacons (Met Office, 2016). Snowdonia is the wettest area with average annual totals exceeding 3000 mm, comparable to those in the English Lake District or the western Highlands of Scotland. In contrast, places along the coast and, particularly, close to the border with England, are drier, receiving less than 1000 mm a year. Over the ten years 2007-2016, average annual rainfall in Wales was 1467 mm with the wettest months in winter (November to January) and the driest in late spring (March and April) and early summer (May), Figure 5. Rainfall and soil water availability may affect the duration of growth through effects on leaf area duration and the photosynthetic efficiency through stomatal closure (Olesen and Bindi 2002).

The availability of water is key for crop productivity and for most crops, which are rain-fed, the pattern of rainfall is important. For example, warm, dry summers reduce crop growth and subsequent yield. Plants can recover from short periods of water shortage that reduce crop canopy expansion during their vegetative stage (reducing the potential for photosynthesis) but longer periods will have a permanent impact on crop yield. Conversely too much rainfall, can cause problems with crop establishment (in autumn) and/or reduce yields (spring/summer rainfall) due to increased disease pressure and low sunlight levels. High rainfall is associated with soil wetness, which can reduce the productivity and versatility of the land and impact on crop productivity/yield (section 3.3.2).

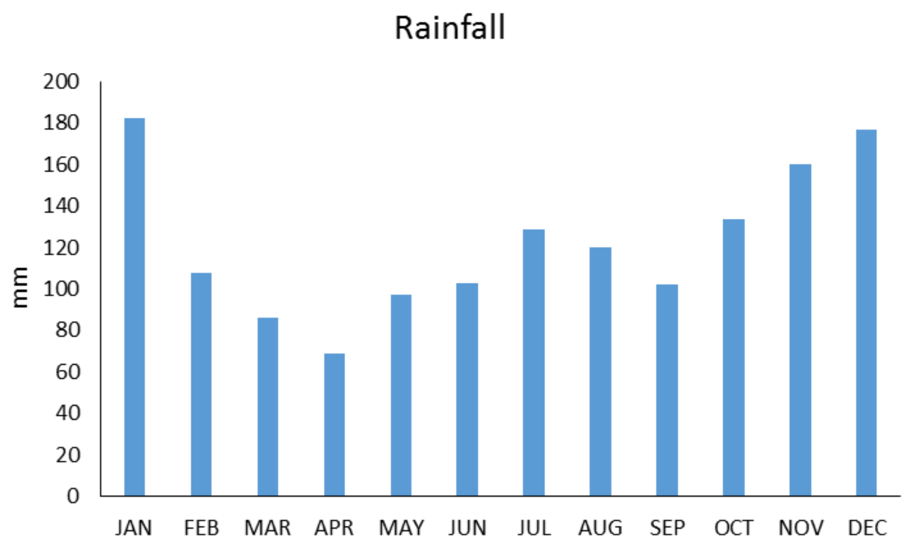

Figure 5. Mean monthly rainfall for Wales (2007-2016).

Site factors

Soil

Soil conditions are strongly influenced by climate (and altitude), vegetation, land use, the sediments or rocks from which they have developed and the underlying geology. Jenny (1941) suggested that soils developed as a result of the interplay of five factors; parent material, climate, organisms, relief/topography and time. Soil characteristics are used to define soils at four levels (major group, group, sub-group and series) in a hierarchical system, general characteristics being used at the highest level to give broad separations and more specific ones at lower levels to give increasingly precise subdivisions. There are 10 major soil groups (based on pedogenic characteristics) within the soil classification for England and Wales, all of which are present in Wales (Avery, 1980), Table 5. These are further divided into >60 groups, >80 sub-groups and 100s of series.

Table 5. Major soil groups in Wales

Major soil group	Land cover (%)	Description
Terrestrial raw soils	<0.1	Very young soils with only a superficial organo-mineral layer
Raw gley soils	0.2	Unripened young soils of saltmarshes
Lithomorphic soils	2.2	Shallow soils without a weathered subsoil
Pelosols	0.1	Clayey 'cracking' soils
Brown soils	30.2	Loamy, permeable soils with weathered subsoil
Podzolic soils	32.3	Acid soils with brightly coloured iron-enriched subsoil
Surface-water gley soils	24.7	Loamy and clayey seasonally waterlogged soils with impermeable subsoil
Ground-water gley soils	3.4	Soils associated with high seasonal groundwater
Man-made soil	0.4	Restored soils of disturbed ground
Peat soils	3.4	Soils in deep peat
Unclassified land (urban)	3.0	

To provide an overview of the soil texture, drainage, fertility, land cover, habitats, topsoil carbon, drainage and general cropping guidance 27 'soilscapes' have been described by Cranfield University. The 'soilscapes' were designed to provide 'extensive, understandable and useful soil data for a non-soil specialist'[4]. There is no direct relationship between the major soil groups in Table 5 and the soilscapes in Table 6, the first classification forms part of an in-depth site specific assessment whereas the latter is intended to give a more broad overview.

The predominant soilscapes in Wales (i.e. those with the largest % land cover) and their agricultural (cropping) characteristics are described in Table 6, below, with the full range of soils shown in Figure 6. Overall, there is a scarcity of high quality agricultural soils, with those considered to be the best and most fertile accounting for no more than 7% of Wales' land area (UK NEA, 2011).

Table 6. The main Soilscapes in Wales (Cranfield University, 2017)

Soilscape description	**Land cover (%)**	**Suitability for cropping**
Freely draining slightly acid loamy soils	24	Suitable for range of spring and autumn sown crops; under grass the soils have a long grazing season. Free drainage reduces the risk of soil damage from grazing animals or farm machinery. Shortage of soil moisture most likely limiting factor on yields, particularly where stony or shallow
Free draining acid loamy soils over rock	23	Land mostly steeply sloping and with restricted mechanised access; suited to grassland with potential for year round grazing
Slowly permeable seasonally wet acid loamy and clayey soils.	15	Mostly suited to grass production for dairying or beef; some cereal production often for feed. Timeliness of stocking and fieldwork is important, and wet ground conditions should be avoided at the beginning and end of the growing season to prevent damage to soil structure. Land is tile drained and periodic moling or subsoiling will assist drainage
Very acid loamy upland soils with a wet peaty surface	9	Some soils are capable of improvement to grassland but most only support rough grazing of low or moderate grazing value
Slowly permeable wet very acid upland soils with a peaty surface	8	Some soils are capable of improvement to grassland but most only support rough grazing of low or moderate grazing value. Grazing or trafficking during wet ground conditions should be avoided to prevent damage to soil structure

[4] http://www.landis.org.uk/soilscapes/soilguide.cfm

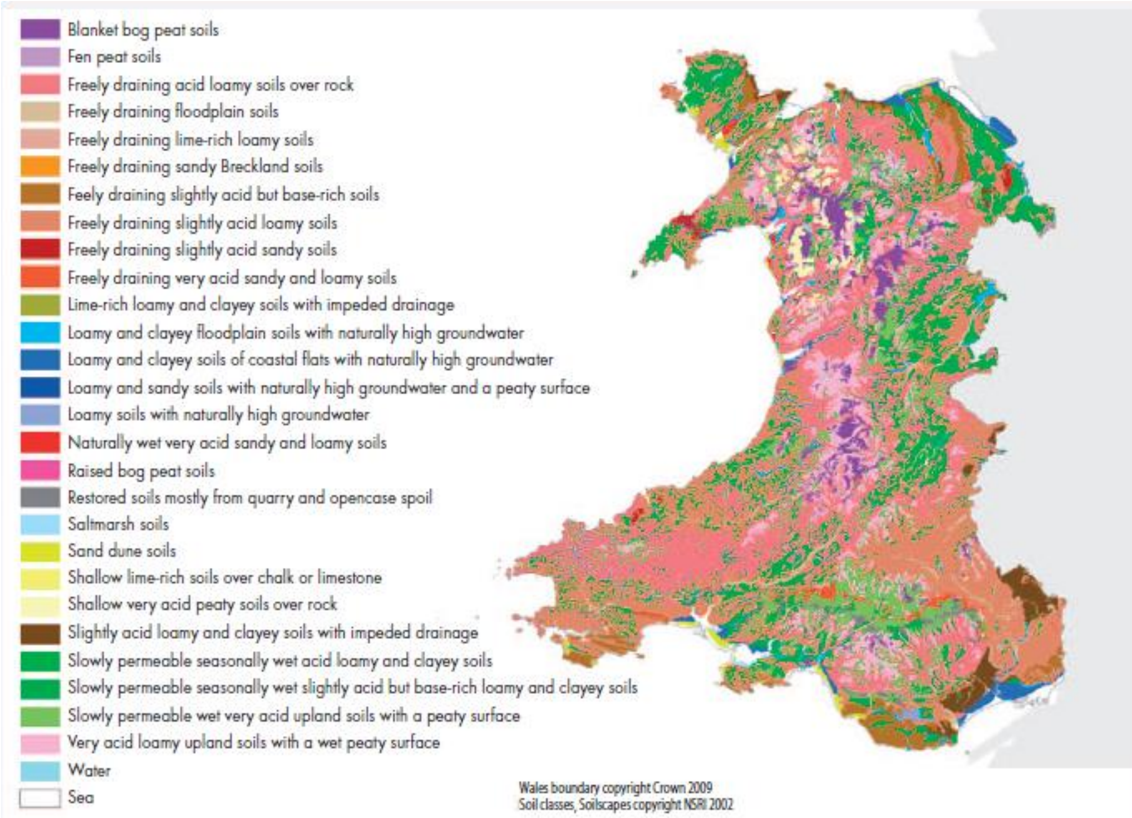

Figure 6. Soilscapes in Wales (Cranfield University, 2017)

Soil pH

Soil pH is a measure of the concentration of hydrogen ions in the soil solution. The lower the pH of soil, the greater the acidity. For most commercial crops the soil pH should be between 5.5 and 7.5 to optimize nutrient availability (Figure 7).

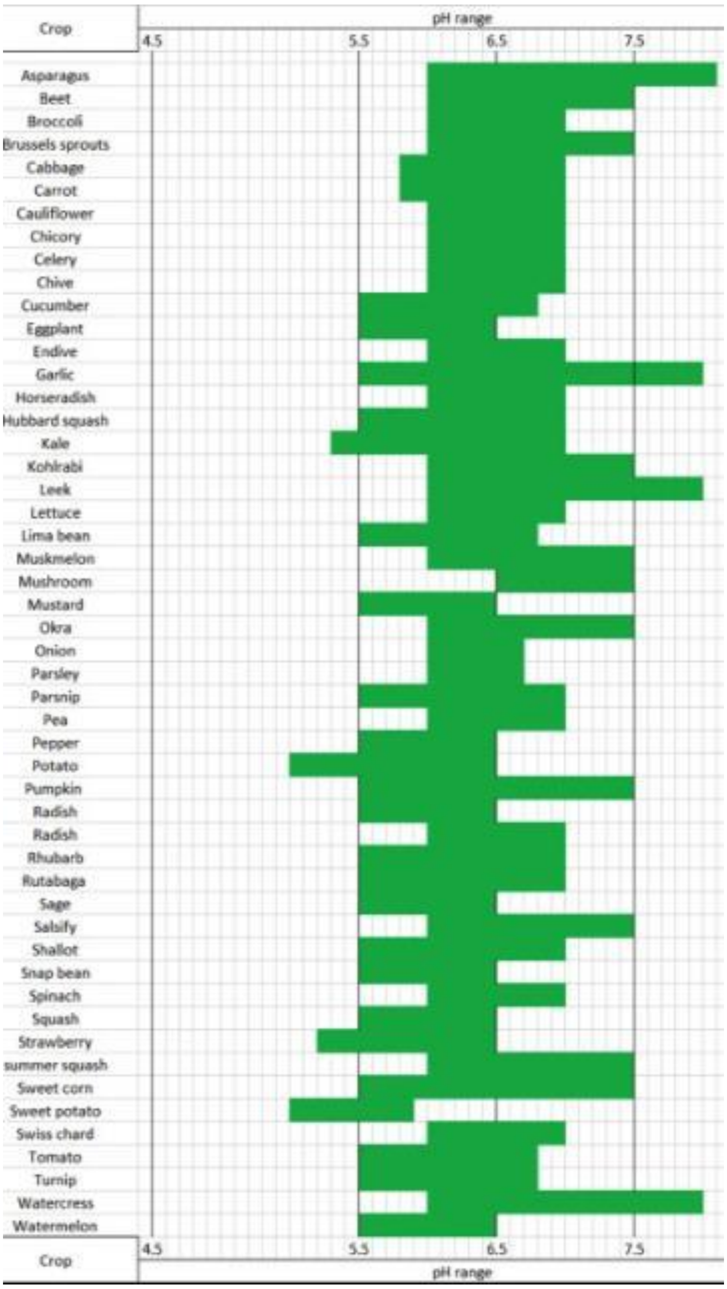

Figure 7. soil pH for selected crop types[5]

The range of pH values for each crop type is listed in the subsequent Sections.

Soil and rooting depth

The growth and development of above-ground plants depends on the acquisition of soil nutrients and water and so are closely associated with root morphology and physiology (Ju *et al*., 2015). Crop species differ in root biomass, root turnover, vertical root distribution, and maximum rooting depth (Canadell *et al*., 1996; Liu *et al*., 2011).

Plant roots provide anchorage and facilitate extraction of water and nutrients from the soil profile. The depth of root growth can be limited by various factors, such as soil bulk density, soil structure, oxygen status, bedrock, water table, so that the deepest roots are mainly found in uncompacted sandy

[5] http://edis.ifas.ufl.edu/hs1207#FIGURE 2

soils where mechanical impedance to root penetration is less than in many other soils (Canadell *et al*., 1996). Rooting depth is the maximum depth from the soil surface to where most of the plant roots can extend during a growing season (van Orshoven *et al*., 2013). Most crops root to a depth of between 60 cm to 1.2 m, although some can extend to greater depths e.g. Sugar beet 140 cm (van Orshoven *et al*., 2013) and Winter wheat to 2 m (Weaver, 1926; reported in Gregory, 1976).

There is a genetically determined maximum depth of rooting although the actual depth of rooting is largely determined by soil conditions (Gregory 1994). The rooting depth increases until anthesis when it usually becomes constant (Gregory 1994). Winter wheat roots reach depths of 0.75-1.0 m by the beginning of April and keep growing rapidly downwards to reach approximately 2.0 m by the end of May (Gregory *et al* 1978).Other work showed that spring barley roots had reached a depth of 0.3 m 60 days after sowing (Welbank *et al* 1974) while maximum rooting depths in barley have been reported as 0.7 m on sandy soils (Madsen 1985), 1.2 m (Bragg *et al* 1984), 1.32 m (Kirby & Rackham 1971), 1.4 m on loamy soils (Madsen 1985), 1.6 m for spring barley and 1.7 m for winter barley (Vetter and Scharafat 1964 cited by Lucas *et al*., 2000). Other studies showed maximum rooting depth for wheat varied from 1.4 m for winter wheat when water availability was high to 1.6 m under drought conditions (Barraclough 1984). Spring wheat (Vetter and Scharafat 1964 cited by Lucas *et al*., 2000) had a depth of 1.6 m compared to 1.9 m for winter wheat (Gregory *et al* 1978; Vetter and Scharafat 1964 cited by Lucas *et al*., 2000). Oat roots penetrate to a depth of 1.8 m (Vetter and Scharafat 1964 cited by Lucas *et al*., 2000). Individual roots of cereal crops can reach a depth of over 2 m (Kirby and Rackham 1971) while laterals can extend to a distance of 1 m from the plant. Fan *et al*. (2016) showed that at least half of the root biomass could be found in the upper 20 cm of soil for all crops (Table 7).

Table 7. Range of root depths (cm) (Fan *et al*. 2016)

Crop	50% of roots	95% of roots	Maximum depth
Wheat	17	104	300
Maize	14	89	240
Oat	11	78	180
Barley	12	97	170
Pulse crops	15	84	100-180
Oilseed crops	9	107	160-180

The rooting depth defines the effective soil depth taking into account any barriers to root extension. Effective depth relates to plant growth and is defined as the vertical distance into the soil from the surface to a layer that essentially prevents further downward growth of plant roots (rock, compacted layer, hardpans and plough pans). Effective depth can also be used to define limitations of drainage and/or water storage as limited by either depth of soil (e.g. to impermeable bedrock) or depth to an impedance layer (e.g. plough pan). In terms of hydrological soil functions, the impact of effective depth varies seasonally. Definitions of soil depth linked to limitation are used by land classification and land capability ratings, where depth is the limiting factor affecting water availability, anchorage or nutrient availability. For example, the Agricultural Land Classification of England and Wales (MAFF, 1988) considers soil depth in relation to its limiting effect on the available water capacity of a soil (Table 8).

Table 8. ALC, limiting depths for soil overlying consolidated or fragmented rock (MAFF, 1988)

Grade/Subgrade	Depth limits (cm)
1	60
2	45
3a	30
3b	20
4	15
5	<15

Drainage

Water is essential for crop production because plants require water for growth and tissue expansion. However, well over 90% of the water required by terrestrial plants is not 'used' in any biochemical way but lost through transpiration (Morison *et al*., 2008). For each crop an assessment of the soil drainage requirement is given in Section 5.

Available water capacity

Soil depth is linked to total available water capacity (total AWC). AWC is the difference between the water contents at field capacity and permanent wilting point in a soil. Total AWC is the average AWC (i.e. soil water content between 0.05 and 15 bar suction and 0.10 and 15 bar for loamy sands) for each horizon based on texture, stoniness and thickness of horizon and the depth of rooting. A shallow soil over consolidated or fragmented rock (other than chalk) cannot supply the water necessary to meet crop demand when transpiration greatly exceeds precipitation e.g. during summer months. However, shallow soils in wetter climatic zones, with suitable texture and structure, can have a high potential throughout the summer months. The concept of easily available water (i.e. soil water content between 0.05 and 2 bar suction and 0.10 and 2 bar for loamy sands) is also used within ALC to account for reduction in a roots ability to extract water as efficiently at depth in the soil. Soil texture is also important with shallow sandy soils holding less water than a silty or loamy soil of the same depth.

The water extracted by plants during wetter months comes from shallow layers where the root density is highest (Canadell *et al*., 1996). However, as these layers dry there is a progressive shift towards deeper water, which allows plants to keep stomata open and extend growth into drier periods (Gardner, 1983). Gregory *et al*. (1978) found that for winter wheat the 3% of roots (by weight) that were deeper than 1 m supplied 20% of the transpired water during dry periods. Where rooting depth is restricted plants may not be able to draw from deeper water reserves and yield potential can be reduced.

Soil wetness

Excessive soil wetness adversely affects seed germination and survival and restricts the development of root systems. Wetness also reduces the temperature of the soil and causes anaerobic conditions. The wetness of the soil affects the sensitivity of the soil to structural damage, influencing the number of days when the site is accessible to farm machinery or for livestock grazing. For ALC purposes, soil wetness is assessed by a combination of the climatic regime, the soil water regime and the texture of the top 25 cm of the soil.

In ALC, the climatic regime is expressed in terms of the mean number of field capacity days (FCD). A soil is said to be at field capacity (FC) following saturation when the larger pores have drained under the force of gravity, which in a meteorological sense is when the soil is at zero moisture deficit (Keay *et al*., 2013). Soils that are poorly or very poorly drained are often found in areas where field capacity endures for long periods.

The soil water regime is determined using the soil wetness class (classes I to VI) (Hodgson, 1976) based on the depth and duration of waterlogging measured by monitoring dip-wells in the field (Jones, 1985). The scale ranges from class I where the soil is not wet within 70 cm for more than 30 days in a year (and is usually recognised by the lack of any mottling) to class VI where the soil is wet within the top 40 cm for more than 335 days in most years. A soil wetness limitation exist where the soil water regime adversely affects plant growth or imposes restrictions on cultivations (MAFF, 1988). Excessive soil wetness adversely affects seed germination and survival, partly by a reduction in soil temperature and partly because of anaerobic conditions. It also inhibits the development of a good root system and can, in extreme cases, lead to plant death.

The timing of soil wetness is key to the impacts on farm practices. Autumn waterlogging can affect drilling/establishment while winter waterlogging (in isolation) has minimal impacts. Spring waterlogging can delay spring drilling, chemical and fertiliser applications, whilst summer waterlogging can lead to reduced grain fill. The spring to summer period is key to determining the degree to which crops can 'recover' from earlier setbacks and ultimate effects on crop yield.

Glycoalkaloid's are naturally occurring toxins within the Solanaceae family (Papathanasiou *et al*., 1989) and waterlogging can affect concentrations in potato crops. If a potato crop is waterlogged for more than a few hours, the centre of the potato turns black as result of oxygen starvation; if the crop remains oxygen starved for more than 24 hours it will begin to rot. In the wet autumn of 2000 up to 10% of the potato crop was still in the ground at any one time compared with 1999 and up to 50% of the over-wintered crop was lost to winter frost (Shepherd *et al.* 2001).

Soil droughtiness

Throughout the growing season it is important for a crop to receive an adequate supply of water to its roots. If at any point the crop demand for water exceeds the capacity of the soil to satisfy this demand, which is defined by Thomasson (1979) as the soil water available to plants (AP), then the crop plants will experience moisture stress and cease to grow. The degree of drought in a soil is influenced by three factors: rainfall amount, evapotranspiration and the store of water available in the soil. Soil droughtiness is determined separately for ALC purposes as a soil can be both waterlogged in the winter but droughty during the summer. The ALC method to assess droughtiness is based on the concept of potential soil moisture deficit (PSMD), which describes the balance of rainfall and potential evapotranspiration (Thomasson, 1979 in MAFF, 1988). Droughtiness limits for ALC grades are defined in terms of moisture balances-MB (mm) for wheat and potatoes, calculated as AP-MD. To be eligible for Grades 1 to 3b the MBs must be equal to, or exceed, the stated minimum values for both wheat and potatoes.

Irrigation

Irrigation demand is greatest in the east and south of England and generally low in Wales because rainfall amounts during the growing season are usually adequate to meet most crop requirements. Also, large areas of Wales have no or little scope for further summer surface water abstractions, whereas the supply of winter surface water poses no problem (EA 2001). In 2001, field vegetables accounted for 27% of the total irrigated area and 26% of the total volume of irrigation water in England and Wales (Downing *et al.* 2003). Because the cost of the irrigated water accounts for only 5-7% of total irrigation costs, demand for water is currently not very responsive to price (Morris *et al.* 2004). In most of Wales, future irrigation demand is expected to remain unchanged, but is predicted to increase slightly in some south-western areas and decrease on Anglesey and in the north-east (Weatherhead *et al*., 1997).

Field capacity days (FCD)

Field capacity days (FCD) is a meteorological parameter which estimates the number of days when the soil moisture deficit is zero. In Wales, soils usually return to field capacity during September or early October, although this can occur as early as August or as late as the end of October, depending on the amount of rainfall. In Wales, the field capacity period usually ends in May (range: mid-April to late June) when evapotranspiration exceeds rainfall and a moisture deficit starts to accumulate.

Jones and Thomasson (1993) suggested that intensive agricultural systems (for crops and livestock) would be adversely affected when average duration of field capacity exceeded 200 days while the effect of wetness on agricultural operations would become very severe when the duration of field capacity exceeded 250 days. More recently, Terres *et al*. (2016) suggested that excess soil moisture was "severely limiting when the number of days with soil moisture content at or above field capacity is greater than or equal to 230 days". Overall, it is generally agreed that, land with over 250 FCD is only suitable for extensive agriculture. In Wales, FCD >250 days is typical, only Anglesey, the Llyn Peninsular, Pembrokeshire, the Newport and Monmouth areas and along the Welsh/English border usually have FCD <250 (Figure 8).

The FCD categories in the ALC for assessing the climatic component of the wetness assessment are, <126, 126-150, 151-175, 176-225 and >225. For Wales, most sites will be in the highest two categories.

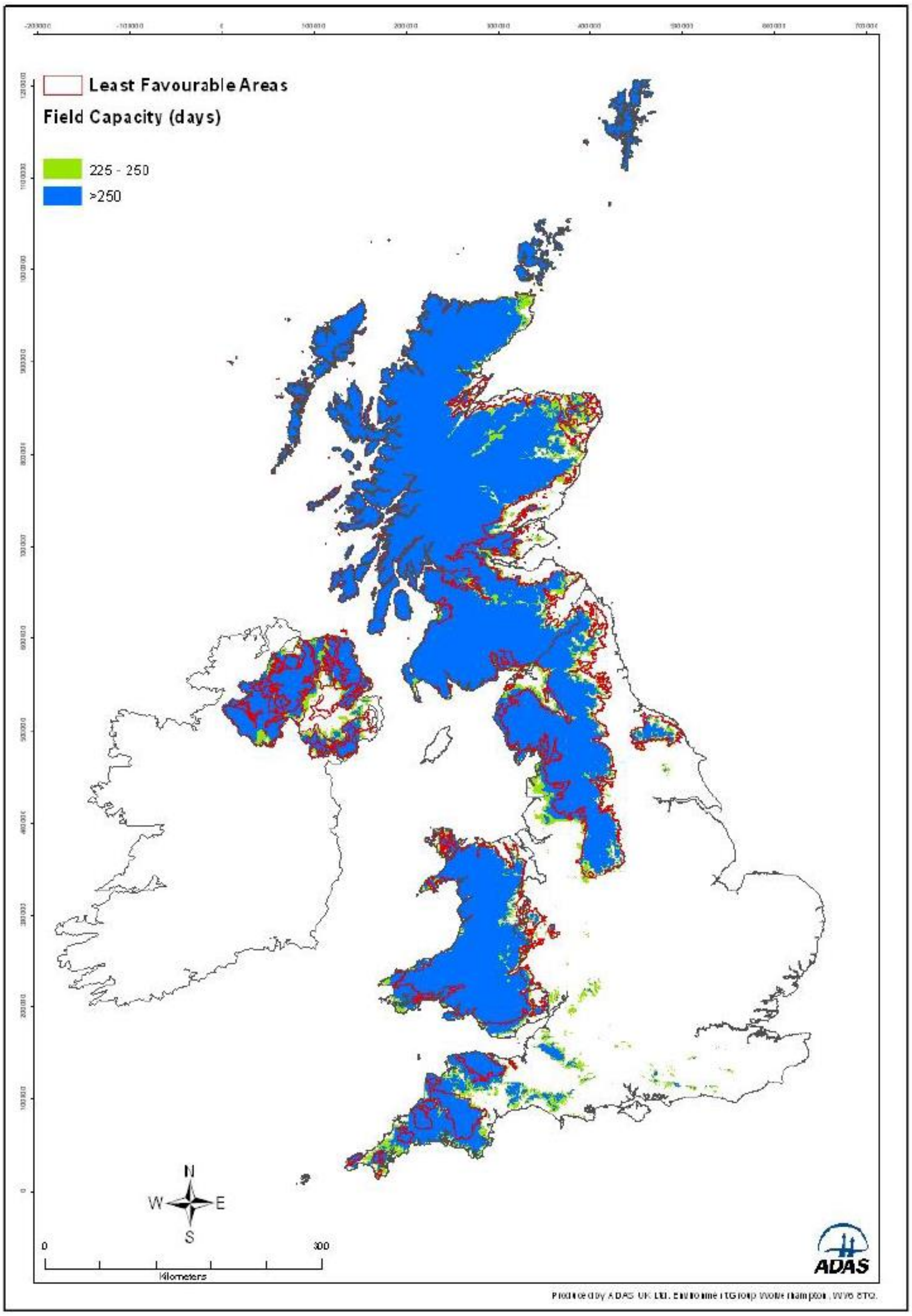

Figure 8. Area of land with 225-250 and >250 days field capacity.

Agricultural Land Classification

The Agricultural Land Classification of England and Wales (MAFF, 1988) provides a framework for classifying agricultural land "according to the extent to which its physical or chemical characteristics impose long- term limitations on agricultural use". The limitations may affect the range of crops which can be grown, the level of yield, the consistency of yield and the associated cost of farming the land. The grade is indicative of the crops that may be potentially grown on that land.

The principal physical factors influencing agricultural production are climate, site and soil. These factors together with interactions between them form the basis for classifying land into one of five grades; Grade 1: excellent quality to Grade 5: poor quality (Table 10). Grade 3 is further divided into two sub-grades designated 3a and 3b. The top three grades (1-3a) are defined in Planning Policy Wales as the 'best and most versatile' (BMV) agricultural land and are suitable for a wide range of crops. The main limiting physical factors are identified as: climate, soil wetness, soil droughtiness, gradient, flooding, soil texture, soil depth, soil stoniness, soil chemical properties and soil erosion. The final ALC grade given to a location is the lowest grade from any of the 10 criteria (i.e. the most limiting factor), with Grade 1 being excellent quality and Grade 5 being of very poor quality.

For maximum yields and minimum costs of production, field vegetables should ideally be grown on Grade1 land (Frost *et al*., 2007). Grade 1 land is located in small pockets of land in North East Wales and South Wales (Figure 9). Similarly, Grade 2 land is located in North East Wales, South Wales, Anglesey and Pembrokeshire. Grade 3 land is more widely distributed and is located in low lying coastal and inland areas, river valleys (e.g. the Wye and Severn) and along the Welsh/English border. Finally, Grade 4 and 5 agricultural land is located in the central upland areas of Wales. Only agricultural land of Grade 3 and above will typically be suited to the tillage and horticultural crops considered in this report.

The climatic criteria are considered first when classifying land. Climate can be overriding in the sense that severe limitations will restrict land to lower grades irrespective of favourable soil or site conditions. In general, limitations to agricultural use increase as rainfall increases and average temperature decreases (Figure 10). For example, for land to be ALC Grade 1, the minimum accumulated temperature is 1300 day °C and the maximum annual rainfall is 1350 mm, Table 9.

Table 9. Minimum accumulated temperature and maximum average annual rainfall for ALC grades 1-4 (and above)

ALC Grade	Minimum accumulated temperature (day °C)	Maximum average annual rainfall (mm)
1	1300	1350
2	1150	1600
3a	1100	1750
3b	1000	1950
≥4	<1000	>1950

Table 10. 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>

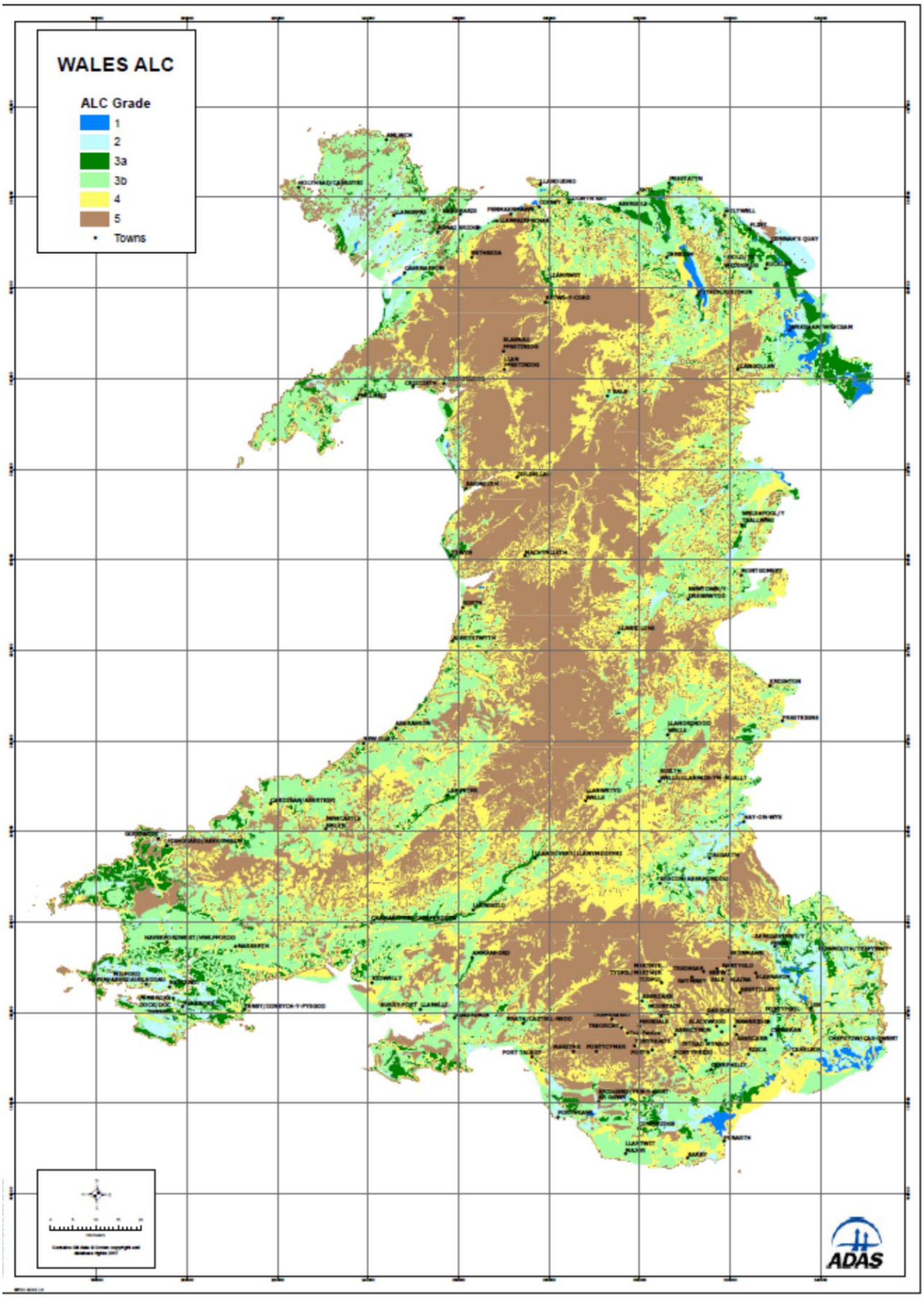

Figure 9. Updated Agricultural land classification of Wales (2017)

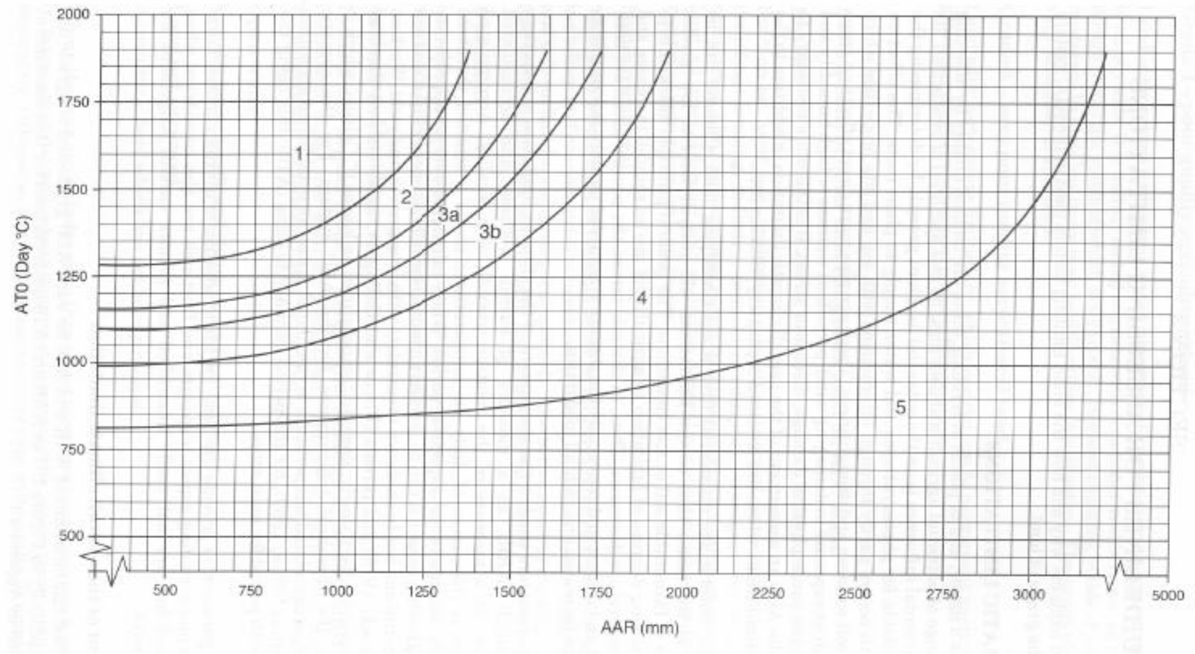

Figure 10. ALC grade according to climate

Crop requirements

Crop 1: Potatoes

More than 170 potato cultivars are commercially grown in England and Wales and classified based on their planting and lifting date into 'earlies' and 'maincrop' (Daccache *et al*., 2012). In Wales, Pembrokeshire Earlies are usually planted in late February to early March and lifted from May to June, while maincrop potatoes are usually planted throughout April and lifted normally after 15–20 weeks. Some seed potatoes are also, grown in Wales, for example, Sarpo Potatoes Ltd, has recently launched the 'Sustainable Potatoes Wales'[6] project, and is hoping to increase the number of Sarpo seed potato growers in Wales.

In 2015, there were *c*.3,000 ha of potatoes grown in Wales (3% of total tillage land), with 60% grown in Pembrokeshire (Welsh Government, 2016), where land is well suited to potato production (Figure 11). Other areas that are potentially suitable for potatoes are in North West Wales and Powys. However, most areas in Wales are either unsuited or marginal for potato growing due to a combination of low temperatures, high rainfall and steep slopes.

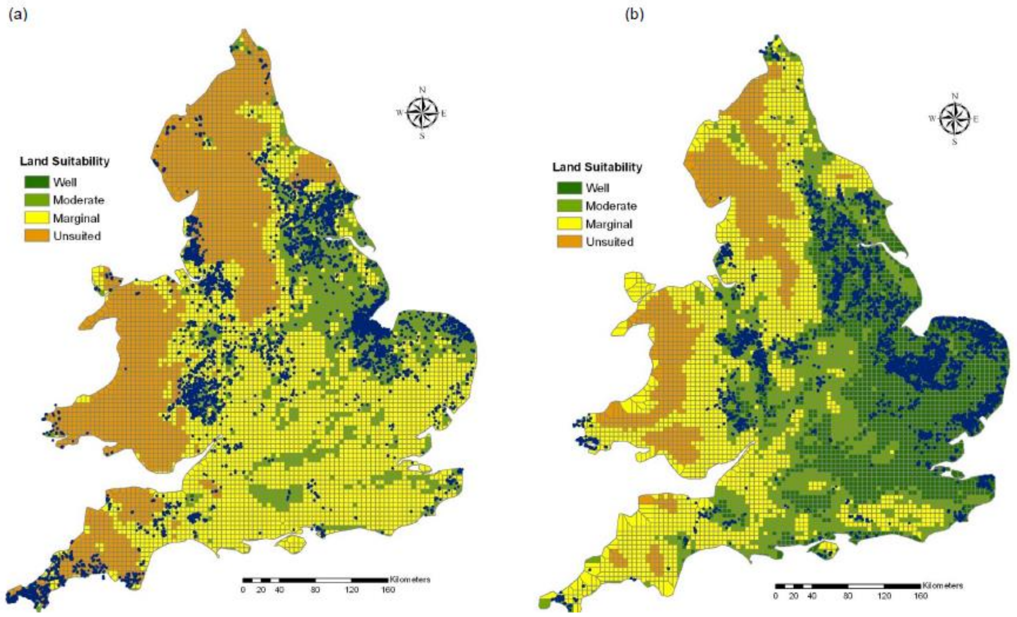

Figure 11. Land suitability for (a) rain-fed and (b) irrigated maincrop potato production (Daccache *et al.*, 2012).

Potatoes are planted in ridges to ensure a well-drained aerated environment for strong growth. The duration of the growth cycle and total tuber production depends on cultivar, temperature and day length. Tuberisation comes before flowering and flowering is not necessary to produce tubers (Quiroz *et al*., 2012).

The shallow and sparse rooting system of potato plants (Opena and Porter 1999) make them sensitive to soil moisture stress (Onder *et al*. 2005) which can reduce yield and affect tuber quality. Potato crops require 0.35 to 0.8 m^3 of water to produce 1 kg of tuber dry matter. Under field conditions, this translates into a water requirement during the growing period of 350 to 650 mm, which is dependent on climate and cultivar (Sood and Singh, 2003 cited by Quiroz *et al*., 2012). Irrigation in England and Wales is mainly applied to enhance quality, e.g. size, shape, appearance, skin condition and delivery time to markets, rather than yield (Morris *et al*., 2004). The viability of commercial potato production

[6] http://sarpo.co.uk/sarpo-potatoes/

is influenced by spatial and temporal variability in soils and agroclimate, and the availability of water resources where supplementary irrigation is required.

Requirement	Min	Max	Notes
Climate			
Day length			Tuber initiation is triggered by short day length and temperatures of 15 to 20°C[7]. However, this response has been out of many commercially produced potatoes.
Growing period (Days)	120	150	Short-lived annual Indeterminate varieties will carry on growing and require desiccation or haulm destruction to maximise yield and tuber quality. Determinate varieties stop producing new growth after tuber initiation. Plant: April (main crop)
Air or ground frost			≤1°C may cause crop stress at any growth stage. Frost will damage juvenile potato plants (emergence to 8 weeks)[8] as the foliage is very sensitive to frost. Emergence should be timed so that the risk of frosts are minimised. Mature tubers are susceptible to frost and must be lifted prior to autumn frosts.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range[9]	15 [7]	25 [30]	Optimum soil temperature 17-20°C AT0 ≥1225°C required for potato production (Jones and Thomasson, 1985).
ALC accumulated temperature (day °C)	1100	>1300	
Rainfall (mm) Optimum & [tolerable] range	500 [250]	800 [1750]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1100°C).
Gradient (°)	0	8.5	Limitations for de-stoning, planting and harvesting machinery (Daccache *et al*., 2012).
Soil			
Soil pH; optimum & [tolerable] range	5 [4.2]	7.0 [8.5]	
Topsoil texture[10]	S	MCL	Wide range of soil types, medium soil type is optimal.

[7] http://www.yara.co.uk/crop-nutrition/crops/potato/key-facts/agronomic-principles/

[8] https://www.daf.qld.gov.au/plants/fruit-and-vegetables/vegetables/temperature-requirements-and-limitations

[9] For cropping tables, this is the mean daily temperature during the growing season

[10] For cropping tables, this indicates the range of suitable soil textures, 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 in Appendix 1.

Soil depth (cm)	20-50	50-150	
Stone content (%)	0	15	Stone free soil is preferred. Stones may be mechanically removed providing they do not exceed 10% (volume) Soils with >15% stones > 6 cm diameter in the top 25 cm are unsuitable (Knox *et al*., 2011)
Drainage			Free draining soils. Water deficit during stolon formation and around tuber initiation can have an adverse effect on yield (Quiroz *et al*., 2012).
ALC soil wetness class	II	I	
Moisture balance (mm)	-20 [-30]	+30 [+10]	
Field capacity (days)	<220	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Risks of diffuse pollution from high rates of fertiliser (N and P application) or pesticides (e.g. 12 fungicide applications[11]) applications. Leaching losses are higher from irrigated than non-irrigated crops. Consider physical factors such as slope when bed forming and ridging. Soil compaction from the use of heavy machinery and/or soil loss through adherence.
ALC group	3a	1	

[11] Garthwaite *et al*., 2014a

Crop 2: Barley

In 2015, 22,000 ha of barley (*c*.70% spring sown) was grown in Wales (25% of total tillage land), of which 17% was malting barley (AHDB, 2016); c.30% of the barley crop was grown in Pembrokeshire (Welsh Government, 2016). The development of barley is governed by temperature, vernalisation (in winter barley varieties) and day length, which determines the duration of the foundation, construction and production phases. Autumn sown varieties require vernalisation to promote subsequent flowering, and for most winter barley varieties a period of vernalisation (0-12°C) advances floral development. Spring-sown varieties lack a vernalisation requirement and can display a weak or strong response to long days (Cockram *et al*., 2007). Barley varieties exhibit a day length response that may influence rate of leaf emergence. Varieties vary in the relative influence of day length and temperature on rate of leaf emergence. However, no current varieties are day length insensitive (AHDB, 2015a.). Winter barley varieties also vary in their vernalisation requirement. When the frost tolerance of cereals was compared in Finland, oat seedlings were the most sensitive followed by barley and spring wheat (Manner, 1967 cited by Lindén *et al*., 1999). Carbohydrate concentration was higher in spring wheat seedlings than in barley or oats indicating a correlation with frost tolerance.

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length			Long days (>12 hours) advance floral development
Growing season (Days)	120-180[12]	270-330	Foundation: 6 months (sowing to start of stem elongation). Growth is slow due to low temperatures, incomplete canopy and dull light. Construction: 2 months. Growth is fast due to complete canopy, bright light and higher temperatures. Production phase: 2 months (Grains fill and ripen).
Air or ground frost			Seedlings susceptible to severe ground frost. Shallow sown winter barley can be susceptible to 'frost heave' over winter where roots are shallow. Cool not freezing temperatures advance flower initiation in winter varieties.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [2]	20 [40]	Sowing to 50% emergence = 150 day degrees Warm conditions speed up development
ALC accumulated temperature (day °C)	1000	>1300	
Rainfall (mm) Optimum & [tolerable] range	500 [200]	1000 [1950]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1100°C). Can be grown at higher altitudes than other cereal crops.

[12] Shorter season is for spring barley, i.e. 120-180 days and longer season for winter barley, i.e. 270-330 days

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. Seven degrees is the ALC limit for grade 1 to 3a land. The limit for 3b land is 11 degrees.
Soil			
Soil pH Optimum & [tolerable] range	6.5 [5.5]	7.5 [8.0][13]	
Topsoil texture	LS	C	Light, medium or heavy soil types. Poorly structured or shallow soils provide weak anchorage and increase root lodging risk. However, where shallow soil is over chalk then roots can penetrate the bedrock.
Soil depth (cm)	50-150	>150	
Stone content (%)	0	35	No specific limits but ALC gives limit values for Grade 3b of 35% and 20% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained However, water stress may limit crop yield (Savin *et al.*, 2012). In particular, late season drought can reduce grain filling (AHDB, 2015a).
ALC soil wetness class	III [II]	I	Winter barley: up to wetness class III on S, LS, SL, SZL, Zl, MZCL, MCL and SCL only. For other soil types wetness class II is limit. Spring barley: wetness classes I and II only.
Moisture balance (mm)	-50 [-55]	+30 [+10]	
Field capacity (days)	<230	<200	
Other			
Environmental risks			Water pollution through over application of nutrients and agrochemicals. Nitrate leaching: apply N appropriately, i.e. only use autumn N on light soils which have been minimally cultivated. Spreading manures and slurry during inappropriate conditions and or in the wrong areas. Soil erosion from late sowing of winter cereals.
ALC group	3b	1	

[13] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=1232

Crop 3: Wheat

In 2015, 22,000 ha of wheat was grown in Wales (25% of total tillage land), 40% of which was grown in South Wales (Welsh Government, 2016). The development of wheat is governed by temperature, vernalisation (in winter varieties) and day length, which determines the duration of the foundation, construction and production phases (AHDB, 2015b). Physiologically, wheat can be categorized according to its response to prolonged periods of cold (vernalisation) and day length (photoperiod). Autumn sown varieties require vernalisation to promote subsequent flowering, and for most winter wheat varieties a period of vernalisation (0-12°C) advances floral development. Spring-sown varieties lack a vernalisation requirement and can display a weak or strong response to long days (Cockram *et al*., 2007). Almost all UK wheat varieties respond to day length. Wheat yield is usually limited by light rather than water (Spink *et al*., 2009). On sunny summer days, growth can be 0.25 t/ha. Clouds reduce light energy by about two-thirds, so on dull days growth is just 0.1 t/ha (AHDB, 2012b). .

Requirement	Min	Max	Notes
Climate			
Day length			Day length affects the duration of foundation and construction phases. Long days (>12 hours) advance floral development in most varieties.
Sunshine hours			Very bright. It is estimated that wheat can only incept 60% of incident light in the UK (Spink *et al*., 2009). Interaction between day length and solar radiation. Southern regions have brighter sunlight; northern regions have longer days.
Growing season (Days)	120-180[14]	280-330	Foundation phase: 6 months (sowing to start of stem elongation - 10% of total growth). Growth is slow due to low temperatures, incomplete canopy and dull light. Construction phase: 2 months (first node to flowering - 50% of total growth). Growth is fast due to complete canopy, higher temperatures and bright light. Production phase: 2 months (Grains fill and ripen).
Air or ground frost			A period of cool temperature 0-12°C advances floral development. Vernalisation reduces the duration of the foundation phase. The apex is frost tolerant. Frost risk highest when the ear is developing Frost risk falls significantly from April (AHDB, 2012b).
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [5]	23 [27][15]	Warmth shortens all phases. More growth occurs in any phase during cool temperatures due to the increase in length of that phase (AHDB, 2012b).
ALC accumulated temperature (day °C)	1000	>1300	
Rainfall (mm) Optimum & [tolerable] range	750 [300]	900 [1600]	For the UK wheat crop, yield losses of 10-20% occur due to drought (Foulkes *et al*., 2001).

[14] Shorter season is for spring wheat, i.e. 120-180 days and longer season for winter wheat, i.e. 280-330 days

[15] Porter and Gawith (1999).

			Drought risk increases from July onwards (AHDB, 2012b).
Site			
Aspect	~	~	
Altitude (m)	~	~	Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1100°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. Seven degrees is the ALC limit for grade 1 to 3a land. The limit for 3b land is 11 degrees.
Soil			
Soil pH Optimum & [tolerable] range	6 [5.5]	7 [8.5][16]	
Topsoil texture	LS	C	Medium or heavy soil types will allow optimal water capture, but wheat can be grown on lighter soils.
Soil depth (cm)	50	50-150	
Stone content (%)	~	~	No specific limits but ALC gives limit values for Grade 3b of 35% and 20% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained Excess water can cause waterlogging during vegetative growth and can reduce yield substantially (Asseng *et al.,* 2012).
ALC soil wetness class	III [II]	I	Winter wheat: up to wetness class III on S, LS, SL, SZL, Zl, MZCL, MCL and SCL only. For other soil types wetness class II is limit. Spring wheat: wetness classes I and II only.
Moisture balance (mm)	-20 [-30]	+30 [+10]	
Field capacity (days)	<230	<200	
Other			
Environmental risks			Water pollution through over application of nutrients and agrochemicals. Nitrate leaching: apply N appropriately, i.e. only use autumn N on light soils which have been minimally cultivated. Spreading manures and slurry during inappropriate conditions and or in the wrong areas. Soil erosion from late sowing of winter cereals.
ALC group	3b	1	

[16] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=2114

Crop 4: Oilseed rape

In 2015, 5,000 ha of oilseed rape was grown in Wales[17] (6% of total tillage land). Oilseed rape typically needs a fine seedbed to ensure good soil contact with the small seeds for rapid germination. Oilseed rape yield is determined by the number of seeds/m^2 and the weight of individual seeds, however, yield potential can only be realised if seeds are completely filled (AHDB, 2015c). The number of seeds per metre squared has been demonstrated to be the most important yield component in oilseed rape accounting for 85% of yield variation (Mendham *et al.*, 1981). This is determined during a critical phase for pod and seed abortion lasting about 300°C days, typically equating to about 19-25 days. Seed filling lasts for a specific period of thermal time, which is extended by cooler temperatures. For example, when the mean temperature is 15°C filling will last *c*.65 days compared to *c*.35 days at 25°C.

Requirement	Min	Max	Notes
Climate			
Day length	~	~	Increased day length and temperatures trigger bud formation.
Growing season (Days)	300 [150]	330 [180][18]	Winter oilseed rape is typically sown between mid-August and mid-September and harvested at the end of July or early August after desiccation. Sowing date is critical as growth prior to winter is an important determinant of yield. However, if plants are sown too early then the risk of frost damage can increase. Spring oilseed rape is sown at the end of March/early April and harvested late August to late September.
Air or ground frost			Yield loss from frost damage to flowers is rare (Spink *et al.*, 2009). Frost damage to leaves may increase the risk of subsequent Botrytis infection.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	15[19] [15]	25 [41]	Sowing to 50% emergence: 160°C thermal time. Seed filling lasts for a specific period of thermal time; cooler temperature extends the duration (AHDB, 2015c).
ALC accumulated temperature (day °C)	1000	>1300	
Rainfall (mm) Optimum & [tolerable] range	500 [400]	1000 [1950]	Increased rainfall during flowering (+100 mm) has been associated with a 6% yield reduction (Peltonen-Sainio *et al.*, 2010)
Site			
Aspect	~	~	

[17] https://data.gov.uk/dataset/cereals_and_oilseeds_production_harvest

[18] 300-330 days for winter oilseed rape; 150-180 days for spring oilseed rape

[19] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=549

Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1100°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. The limit for 3b land is 11°.
Soil			
Soil pH Optimum & [tolerable] range	6.5 [5.5]	7.6 [8][20]	
Topsoil texture	S	C	Medium or light soils are best, heavier soils are also suitable providing they are well drained.
Soil depth (cm)	50-150	50-150	Deep rooting to >100 cm is important for maximising seed filling in dry conditions (AHDB, 2015c).
Stone content (%)	0	35	No specific limits but ALC gives limit values for Grade 3b of 35% and 20% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained. Oilseed rape is more sensitive to poor seed filling conditions than wheat.
ALC soil wetness class	III [II]	I	Up to wetness class III on S, LS, SL, SZL, Zl, MZCL, MCL and SCL only. For other soil types wetness class II is limit.
Moisture balance (mm)	-50 [-55]	+30 [+10]	
Field capacity (days)	<230	<200	
Other			
Environmental risks			Water pollution through over application of nutrients and agrochemicals. Nitrate leaching: apply N appropriately, i.e. only use autumn N on light soils which have been minimally cultivated. Spreading manures and slurry during inappropriate conditions and or in the wrong areas. The inappropriate use of slug pellets, i.e. metaldehyde slug pellets must not be allowed to fall within 10 metres of any field boundary or watercourse.
ALC group	3b	1	

[20] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=549

Crop 5: Maize

In 2015, *c.*10,500 ha of maize was grown in Wales (12% of total tillage land) predominately in North East and South Wales (Welsh Government, 2016). Maize is a sub-tropical plant and site selection is one of the most important factors to take into consideration when deciding whether and where to grow the crop. Factors such as temperature, soil type and topography, moisture and altitude are all important for crop growth. The cooling effect linked to increasing altitude limits maize growing to fields below 305 m (1000 feet) in most circumstances.

Maize seeds germinate at 8-10°C and so drilling should only take place once the minimum soil temperature reaches a consistent 8°C over a period of 7 consecutive days (Farming Connect, 2014). In addition, over a complete growing season a maize crop needs a set amount of solar energy in order to develop from germination through to harvest (Phipps *et al.*, 1974). This is typically measured in Ontario Heat Units (OHUs) which are calculated by using the maximum daily air temperature above 10^{o}C and the minimum daily air temperature below 5^{o}C, between 1 May to 31 October 31 (University of Reading, 2014). OHU requirements for successful forage maize growth have been estimated to be about 2,300 units (Phipps and Wilkinson, 1985).

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length	~	~	Day neutral plant.
Growing season (Days)	150	200	Drilled in late April or early May depending on soil temperature and harvested mid-September to mid-October.
Air or ground frost	-3	0	Avoid frost pockets. The crop is susceptible to frost damage. A crop at the 2-6 leaf stage can be delayed 2-3 weeks by a late May frost. Early frost:≤-3°C death of growing point Late frost:≤-0°C leaf necrosis
Other			Sheltered from wind
Mean daily air temperature (°C). Optimum & [tolerable] range	18 [10]	33 [47]	Maize seeds germinate at soil temperature of 8-10°C. (University of Reading, 2014). 2,300 OHU between 1 May and 31 October.
ALC accumulated temperature (day °C)	1100	>1300	
Rainfall (mm) Optimum & [tolerable] range	600 [400]	1200 [1750]	
Site			
Aspect			South facing sites best for early drilling. North facing slopes are only suitable if they warm to 8°C by mid-May (Phipps and Wilkinson, 1985).
Altitude (m)	0	305	Site >180 m are marginal and only likely to be suitable with lighter, drier soils (Limagrain, 2010).
Gradient (°)			Avoid steeply sloping fields.
Soil			
Soil pH Optimum & [tolerable] range	6	8	pH 6.8 ideal (Limagrain, 2010).
Topsoil texture	S	SCL	Wide variety of soil types but medium textured are best.

			Heavy wet soils are slow to warm and can delay drilling; erosion risk is higher on sandy and light silty soils. Soil type will influence drilling and harvest date.
Soil depth (cm)	100	>200	Shallow soil will impair root development and yield. Rooting depth is typically between 150 and 200 cm.
Stone content (%)	0	15	No specific limits but ALC gives limit values for Grade 3a of 15% and 10% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Maize seeds and seedlings require moisture to enable germination and ongoing development. Maize is sensitive to water stress and due to its high determinacy it cannot easily recover the loss of productivity (Hsiao and Fereres, 2012).
ALC soil wetness class	II	I	
Moisture balance (mm)	-20 [-30]	+30 [+10]	
Field capacity (days)	<220	<200	
Other			
Environmental risks			Ground cover is slow to establish after drilling increasing the risk of soil erosion and/or run-off. Buffer zones are required around all field margins. Highest risk of erosion on sloping land with light soil. Heavy harvest machinery can damage soil structure leading to compaction. Late harvesting reduces the chance to establish a cover crop and so erosion and sediment run-off can occur. Water pollution through over application of nutrients and agrochemicals. Spreading manures and slurry during inappropriate conditions and/or in the wrong areas.
ALC group	3a	1	

Crop 6: Asparagus

Asparagus is a niche, high-value crop which has increased in popularity in recent years. It is a perennial crop with relatively high establishment costs but once established will last 10 years (Creed *et al.*, 2014). Following a 2-3 year establishment phase asparagus is typically cropped from late April to mid-June. Cutting beyond the end of June would not allow the ferns to grow and restore the starch in the crop for the following harvest (Red Tractor Assurance, 2016a). Irrigation is essential when establishing the crop from container-raised transplants but is not needed for established plants.

Requirement	Min	Max	Notes
Climate			
Day length	~	~	Shortening day length induces crown carbohydrate accumulation and senescence.
Growing season (Days)	210	270[21]	Crop will be established in the field in April, typically using one-year old asparagus crowns (often imported from Holland) and cropping will begin after two to three years (end of April to mid-June).
Air or ground frost			Susceptible Frost will damage new spear growth in the spring, which can result in the crop being out of production for up to 7 days (Red Tractor Assurance, 2016a). Frost can cause premature fern death in the autumn.
Other			Well sheltered sites are preferred. Wind can bend spears in harvesting season reducing crop quality. Wind can break fern later in the year reducing photosynthetic potential (Red Tractor Assurance, 2016a).
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [6]	30 [38]	Low temperatures are required for about 90-150 days per year between late autumn and spring[21].
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	800	1200 [1600]	
Site			
Aspect			South facing
Altitude (m)			No physiological limits to growth at high altitudes proving other requirements are met. However, land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1100°C).
Gradient (°)	0	4	Flat site
Soil			

[21] http://ecocrop.fao.org/ecocrop/srv/en/cropView?id=468

Soil pH Optimum & [tolerable] range	6 [4.5]	6.7[21] [8.2]	Where the pH is above 7 micronutrient deficiency may occur (Red Tractor Assurance, 2016a).
Topsoil texture	LS	MZCL	Loamy sand, sandy loam, silty loam, sandy silt loam, sandy clay loam and silty clay loam. Heavy clay soil is not suitable. Sandy soil may be prone to slumping and compaction due to harvest traffic (machinery and workers).
Soil depth (cm)	50	150	
Stone content (%)	0	10	Avoid stony soils as emerging spears may be damaged by stones. No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Avoid soils which are poorly drained or with a high water table. Waterlogging in winter increases the spread of soil borne diseases and can also cause significant root death. The crop can respond to drainage on light land even when established.
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Sloping sites can be prone to soil erosion. Soil slumping and/or compaction after the harvest season when site traffic (workers and machinery) is high (up to 50 visits). Soil removal by adherence to machinery. Water pollution from agro-chemicals and or fertiliser.
ALC group	2	1	

Crop 7: Cauliflower

Cauliflower can be harvested all year round in the UK by growing in production areas with different temperatures and using varieties with different maturity types that mature in early summer, summer/autumn and winter through to spring:

- *Early summer cauliflower* (sown in October and over-wintered in cold glass or sown in a heated glasshouse in January to early March)
- *Late summer and autumn cauliflower* (sown in March to April; transplanted in June/July and harvested in Sep-Dec)
- *Winter cauliflower* (maturing from December to May). These are very susceptible to frost and mainly grown in coastal areas of Kent and south west England.
- *Winter hardy cauliflower – spring heading* (mature March to June.

Continuity of production within each maturity period is manipulated by planting many different cultivars which mature at slightly different times. Evolution, breeding and selection have resulted in many cultivars of each type being appropriate for its specialised thermal environment (Red Tractor Assurance, 2016b). Cauliflower is described as a very demanding crop for water (Nieuwhof 1969 cited by Defra, 2008). There is no particular drought sensitive phase, but reduced water will result in reduced yield.

Cauliflowers are grown in rotation with early potatoes in Pembrokeshire and would suit production in other parts of the country particularly in coastal regions (Creed *et al*, 2014).

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length	~	~	Long days (>14 hours) induces flowering.
Growing period (Days)	60	120	Transplanted from February/March through to July (in the southwest of England) Harvest from May to December depending on heading date.
Air or ground frost	-10	-5	Moderately susceptible. Winter cauliflower are very susceptible to frost. Winter hardy cauliflower (spring heading) are frost tolerant; -5 to -10°C for short periods.
Other			In wet areas expose to prevailing winds to dry crop quickly and prevent the spread of disease. Coastal (e.g. west coast of Wales).
Mean daily air temperature (°C). Optimum & [tolerable] range	10 [5]	25 [30]	Transplanting-curd initiation: mean temperature >7.5°C, minimum temperature >0°C. Curd growth phase: mean temperature 9-20°C, minimum temperature >5°C (Kenny *et al.,* 1993).
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	600[22] [450]	1100 [1600]	
Site			
Aspect			Sloping to the south and west. Avoid valley bottoms or frost susceptible areas.
Altitude (m)	30	60	Winter cauliflower ≤90 m (Red Tractor Assurance, 2016b).

[22] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=553

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. The limit for 3b land is 11°.
Soil			
Soil pH Optimum & [tolerable] range	7 [6.5][22]	7.5 [8.5]	Particularly important when club root may be a problem.
Topsoil texture	S	MCL	Wide range of soil types providing they are well drained, have good structure and allow good rooting. Light sandy soils require irrigation.
Soil depth (cm)	20-50	>150	Cauliflower is not deeply rooted – although there is variation between cultivars.
Stone content (%)	0	10	No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained Irrigation may be needed in South and East during periods of drought (Red Tractor Assurance, 2016b).
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Pollution of watercourses with pesticides; 5 m buffer zones are required for some sprays. Potential soil structural damage caused by harvesting winter cauliflowers on heavier soils. Disposal of perforated polythene crop covers. The inappropriate use of slug pellets, i.e. metaldehyde slug pellets must not be allowed to fall within 10 metres of any field boundary or watercourse. Excess or untargeted nitrogen use. Applications of N to cauliflower are high (c.200 kg N/ha). Crop residues are high in N and ploughing in can increase the risk of nitrate leaching.
ALC group	2	1	

Crop 8 & 9: Squash and courgette

Squash and courgettes are members of the *Cucurbitaceae* family. There are two main groups: 1) summer cucurbits including courgettes, marrows and Gem squashes and 2) winter squashes, which are grown to full maturity and picked when the skin is set (e.g. Butternut squash or pumpkin) (Red Tractor Assurance, 2016c). To achieve the best yields pollinators should be actively encouraged into the crop, for example by bringing hives into the crops or planting wildflower mixtures to attract bees.

Requirement	Min	Max	Notes
Climate			
Day length	~	~	Most are day neutral.
Growing period (Days)	40	100	Planted under protection from early April or without protection from mid-May to mid-July. Courgettes and marrow are often produced from sequentially drillings/plantings. Harvest: mid-June to end of October.
Air or ground frost			Very susceptible to frost at all stages[23]. Frost free area required.
Other			Good wind protection. Sites prone to high winds should be avoided.
Mean daily air temperature (°C). Optimum & [tolerable] range	17 [6]	30[24] [40]	
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	600 [300]	1500 [1600]	
Site			
Aspect			South facing
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1150°C).
Gradient (°)	0	7	Slight slopes. 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	5.5 [4.5]	6.8 [8.3]	6.5 is the target pH.
Topsoil texture	S	SCL	A range of soil types can be used. Moisture retentive soils are suitable for the planted crop but can impair emergence of early direct drilled crops.
Soil depth (cm)	20-50	50-150	Deeper soil optimal for squash (>150 cm)

[23] https://www.daf.qld.gov.au/plants/fruit-and-vegetables/vegetables/temperature-requirements-and-limitations

[24] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=821

Stone content (%)	0	10	Stony soils may be ok for crop establishment but will impair crop quality as the crop trails. No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Most crops will require irrigation to achieve Class 1 yields
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Water pollution through over application of nutrients and agrochemicals. Spreading manures and slurry during inappropriate conditions and or in the wrong areas.
ALC group	2	1	

Crop 10: Parsnips

Well-drained, deep soils are required for parsnips with a loose, sandy texture without stones to enable optimal development of the root. Compared to carrots, parsnips are more sensitive to acidic soils and ideally require a pH between 6.0 and 6.8 (CALU, 2007b). Parsnips do not need full sun exposure and can be grown in lightly shaded plots. Early sown crops may be slow to germinate and more uniform germination will result from crops grown after the last risk of frost (Red Tractor Assurance, 2016d). Parsnips can be kept in the soil over winter; exposure to frost will turn the carbohydrates into sugar making them taste sweeter.

Requirement	Min	Max	Notes
Climate			
Day length			Biennial, long day plant.
Growing period (Days)	210	300	First early crops are seeded in autumn/winter under plastic to warm the soil and harvested in June. Main crops are sown from February to early June and harvested in August to April
Air or ground frost			Mainly frost tolerant, susceptible, only at emergence. Over-wintered 'early' crops can suffer from frost damage leading to forking and lateral hairs (Red Tractor Assurance, 2016d). Flavour and sweetness are improved by frosting (Soffe, 2016).
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [5]	21[25] [25]	
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	500 [300]	800[25] [1100]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1150°C)
Gradient (°)	0	7	Limitations for de-stoning, planting and harvesting machinery. 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	6 [5.8]	6.8[25] [8.3]	5.8

[25] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=1642

Topsoil texture	S	SL	Sand to sandy loams are usually most suitable. Some silt soils are also suitable but may be restricted by winter access issues. Soil pans and compaction will restrict root growth and should be avoided. Heavy and peaty soils make harvesting of clean roots difficult (Soffe, 2016).
Soil depth (cm)	50-150	>150	Deep.
Stone content (%)	0	10	Stone separation and burying will be required if soils are stony to avoid root damage and malformation. Soils with a high content of gravel that cannot be removed are unsuitable. No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained Drought tolerant crops. However, drought stress can affect skin quality.
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Potential soil structural damage from use of soil separation equipment in wet conditions Disposal of polythene and or fleece crop covers. Agrochemicals can leach through the light soils commonly used to grow parsnips. Nitrate leaching, although parsnips have relatively low N inputs and have high N use efficiency as result of their deep roots. Root crops are at risk from water erosion, due to large areas of bare soil.
ALC group	2	1	

Crop 11: Carrots

Carrots are best grown on soils that are light and sandy in texture (sand to sandy loam). However, these soils types can be stony and mechanical stone separation will be required in order to grow good quality carrots, avoid forking and minimise stone damage (Red Tractor Assurance, 2016e). Over wintered carrots are drilled in October (typically covered) and harvested in June/July. In comparison, main and late season crops are sown between February and June and harvested from August to May. Carrots are susceptible to frost damage whilst in the ground and are often covered by straw while in field storage to prevent loss. Most carrot crops will require irrigation, due to the small amounts of water available for growth in light sandy soils.

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length	~	~	Biennial, day neutral or long day plants.
Growing season (Days)	150	210	Early crops: seeded in late autumn or winter and covered in plastic or fleece to warm the soil. After covers are removed water and nutrients are applied to prevent checks to growth. Harvests in June and July. Main crop: sown February to June and harvested from August onwards (Red Tractor Assurance, 2016e).
Air or ground frost			Moderately susceptible (emergence to 8 weeks)[26].
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [15]	24 [30]	Ideal soil temperature for germination is 10°C (CALU. 2007a). Root growth is fastest at 15-18°C.
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	600 [400]	1200[27] [1600]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1150°C)
Gradient (°)	0	7	Limitations for de-stoning, planting and harvesting machinery. 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	5.8 [4.2]	6.8 [8.7]	

[26] https://www.daf.qld.gov.au/plants/fruit-and-vegetables/vegetables/temperature-requirements-and-limitations

[27] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=871

Topsoil texture	S	SL	Sandy to sandy loam soils are best. Light silts and light, loamy peats are also suitable.
Soil depth (cm)	50-150	50-150	Dense rooting system with main nutrient/water uptake roots < 60 cm depth (Landon, 1991).
Stone content (%)	0	10	To avoid getting forked roots, the soil should be stone free (CALU, 2007a). Stone separation and burying will be required if soils are stony to avoid root damage and malformation. Soils with a high content of gravel that cannot be removed are unsuitable. No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained. Avoid soils with impeded drainage due to soil pans or compaction. Irrigation is often needed to prevent wet/dry cycles which may result in splitting or misshapen roots.
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Potential soil structural damage from use of soil separation equipment in wet conditions Disposal of polythene and or fleece crop covers. Agrochemicals can leach through the light soils commonly used to grow carrots. Nitrate leaching, although carrots have relatively low N inputs and have high N use efficiency as result of their deep roots. Root crops are at risk from water erosion, due to large areas of bare soil.
ALC group	2	1	

Crop 12: Celeriac

Celeriac originates in the Mediterranean and has warm temperate growth requirements. Celeriac is a biennial crop, which grows vegetatively from seed in the first year into a swollen stem storage organ following leaf senescence in the autumn. Optimal temperatures for growth are between 15 and 25°C and growth stops at <7°C and >24°C. Cold sites (e.g. north facing or shady) should be avoided and harvest must be completed before the first frosts in autumn (Red Tractor Assurance, 2016f).

Celeriac should be grown in a well-structured, free draining soil and similarly to other root crops, soils must not contain excessive stones or compaction. It is particularly sensitive to boron deficiency which will result in hollow swollen stems. However, crop toxicity may occur when soil boron is >4 mg/l.

Requirement	Min	Max	Notes
Climate			
Day length	~	~	Biennial, flowering induced by low temperature and long days.[28]
Growing period (Days)			Warm temperate growth requirements with an optimal range of 15-18°C. Growth ceases at <7°C and >24°C.
Air or ground frost			Cold sites should be avoided. Celeriac can suffer frost damage at ≤-1°C. Sites prone to late spring or early autumn frosts should be avoided.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [7]	20 [24]	
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	1000 [700]	1200 [1600]	
Site			
Aspect			South facing fields are best.
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1150°C)
Gradient (°)	0	7	Limitations for planting and harvesting machinery. 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	6.5 [5.3]	7.0 [8.3]	Yield may decline if the pH is <6.3. Boron deficiency may occur if the pH is >7.
Topsoil texture	SL	SCL	Medium. Sandy loams, sandy clay loam and silts.

[28] Booij and Meurs, 1995.

			Where irrigation is not available, moisture retentive silts are best. Soils must not be poorly drained and a good soil structure is essential. Compaction or soil pans will impede root growth.
Soil depth (cm)	50-150	50-150	
Stone content (%)	0	10	A stone free soil is best to prevent damage to roots. No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained, but may tolerate wet spells. The absence of irrigation may lead to stop-start growth with resulting hollow stems.
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Potential soil structural damage from use of soil separation equipment in wet conditions. Agrochemical or nitrate leaching. Disposal of polythene and or fleece crop covers.
ALC group	2	1	

Crop 13: Onions

Soil type and latitude influence the production system and the quality of the onions. The most suitable soil types are sandy loams to sandy clay loam and some silts. Soil must not be stony and should be well drained (Red Tractor Assurance, 2016g). Soils should be well-drained, deep, moisture-retentive, stone free and free-working (Soffe, 2016). Most onions are grown in eastern England as warm, sunny conditions are needed for quality and ease of harvesting (Soffe, 2016). Onions can be over-wintered or planted in spring as seeds or onion sets and harvested in June/July (over-wintered) or July-September (spring). Bulb formation is influenced by day length (requires 12-15 hour long days) and hence site selection is influenced by latitude.

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length			Bulb formation is influenced by day length and site selection should take into account latitude. 12-15 hour day length promotes bulb formation. Direct drilling is more successful for crops south of the Humber. Further North, establishment is from sets or modules.
Growing period (Days)	150	210	Over-wintered: seeded or planted as sets in autumn and harvested June/July the next year Spring planted sets: harvested in July/August Spring planted seeds: harvested in late August/September Bulb formation requires 12-15 hour long days
Air or ground frost	-8	-6	Moderately susceptible (emergence to 10 weeks)[29] They can survive at temperatures of -6°C, but are killed when conditions drop below -8°C.[30]
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	12 [4]	25 [30]	Optimum germination and emergence of onion seed at 12-28°C[30]
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	350 [300]	600[31] [1600]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1150°C)
Gradient (°)	0	7	Limitations for planting and harvesting machinery. The safe and efficient use of machinery on sloping land depends very much on the type and design of the

[29] https://www.daf.qld.gov.au/plants/fruit-and-vegetables/vegetables/temperature-requirements-and-limitations

[30] http://www.yara.co.uk/crop-nutrition/crops/onion-and-garlic/key-facts/agronomic-principles/

[31] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=364

			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 [4.3]	7.0[31] [8.3]	
Topsoil texture	SL	SCL	Medium Sandy loam to sandy clay loam, very fine sandy loam and some peat based soils. Sensitive to salinity so saline soils should be avoided.
Soil depth (cm)	20-50	50-150	Rooting is generally poor with short lengths and few root hairs. Shallow system concentrated in top 30 cm (Landon, 1991).
Stone content (%)	0	10	Stones will hinder growth and harvesting efficiency and stony soils are best avoided. No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained Free from compaction and well drained. Irrigation is essential on sand and lighter soil types.
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Excess or ill-timed N applications could lead to leaching to ground water. Shallow rooting leads to low N use efficiency, which increases risk of leaching. High agrochemical applications (12 spray rounds per annum[32]) lead to an associated risk of diffuse pollution. Risk of soil erosion due to bare soil particularly after seedbed preparation and during harvest.
ALC group	2	1	

[32] Garthwaite *et al*., 2015

Crop 14: Leeks

Traditional long-season leeks are a renowned Welsh crop already successfully grown on various scales (Creed *et al*., 2014). Leeks can be grown on a wide range of soil types but the most suitable are sandy loam to sandy clay loams that drain well. Leeks can be either 1) drilled in late spring, over-wintered and harvested from January to May, 2) spring planted transplants for harvest in July/August or 3) spring drilled from seed for harvesting in August-December (Red Tractor Assurance, 2016h).

Leeks may require irrigation during the germination period if the soil is very dry. In addition, transplanted leeks will need watering immediately after planting to ensure establishment (CALU, 2007c).

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length			Long day (12-15 hours) promotes bulb development.
Growing period (Days)	120	150	Over-wintered: planted in late spring and harvested January to May Spring planted: harvest in July/August (sown as transplants) or August to December (drilled)
Air or ground frost		-1	Emergence to 10 weeks, moderately frost sensitive[33].
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	18 [6]	24[34] [27]	
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	750 [350]	1000 [1600]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1150°C)
Gradient (°)	0	7	Limitations for planting and harvesting machinery. 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 [4.5]	6.5[34] [7.5]	Very sensitive to soil acidity. However, on peaty soils the pH will not generally restrict growth unless below 6.0.
Topsoil texture	SL	SCL	Most suitable are sandy loam to sandy clay loam, silts and high organic matter peat based soils. Irrigation may be required.

[33]https://www.daf.qld.gov.au/plants/fruit-and-vegetables/vegetables/temperature-requirements-and-limitations

[34] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=363

Soil depth (cm)	20-50	50-150	
Stone content (%)	0	10	No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained High requirement for water therefore land without access to water should be avoided. But soils that drain poorly should be avoided.
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Excess or ill-timed N applications could lead to leaching to ground water. Leeks have higher N application rates than onion and consequently a greater risk of nitrate leaching. Shallow rooting leads to low N use efficiency, which increases risk of leaching. High agrochemical applications (12 spray rounds per annum[32]) lead to an associated risk of diffuse pollution. Risk of soil erosion due to bare soil around particularly after seedbed preparation and during harvest.
ALC group	2	1	

Crop 15: Rhubarb

Rhubarb will grow well on most soil types as long as they are well drained. Some of the more temperate Welsh coastal sites around Pembrokeshire and the Llŷn peninsula would be good for early harvesting and could be harvested as early as late February in a good year (Creed *et al*., 2014).

Rhubarb is a perennial and remains in the field for many years and thus careful site selection is essential (Red Tractor Assurance, 2016i). It can normally be harvested in the second year after planting and may continue to yield for 5-6 years. Fields with known problems with stem nematodes or perennial weeds should be avoided as soil cultivations are limited once the rhubarb crop is established (Red Tractor Assurance, 2016i).

Irrigation may be required to help establishment in newly planted crops and in dry summers; in the forcing shed irrigation will typically be carried out weekly.

Rhubarb for forcing should be grown on sites which allow machine access from November to January. In addition, soil temperature at 10 cm depth needs to regularly go below 5°C from October onwards before crowns can be lifted for forcing. Rhubarb for forcing typically spends two years growing in the field before being transferred into heated sheds in November where it is kept in the dark. Horticulture Wales (undated) previously concluded that forced rhubarb was “a specialist crop which is unlikely to be a commercially viable proposition in Wales, as it is strongly linked to a particular geographical area with the requisite climate, soils, natural resources and skill base”. In contrast, Creed *et al.* (2014) concluded that “forcing the crop provides a value added option for production”.

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length	~	~	Temperatures <5°C are required to break dormancy and stimulate spring growth.
Growing period (Days)			Harvest: forced crop, December to March. Harvest: field crop, late May to early June in the field.
Air or ground frost			Rhubarb is frost tolerant. For forced crowns exposure to cold temperatures during October and November is required.
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range	15 [5]	24 [30]	Soil temperature at 10 cm depth needs to regularly go below 5°C from October onwards before crowns can be lifted for forcing.
ALC accumulated temperature (day °C)	1150	>1300	
Rainfall (mm) Optimum & [tolerable] range	800 [400]	1300 [1600]	
Site			
Aspect			
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1150°C)
Gradient (°)	0	7	Limitations for planting and harvesting machinery. 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	6.5 [5.3]	7 [7.8]	> 5.8 on peat soils.
Topsoil texture	S	SC	Any soil providing it has good moisture retention and is well drained.
Soil depth (cm)	50-150	50-150	
Stone content (%)	0	10	No specific limits but ALC gives limit values for Grade 2 of 10% and 5% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained Cold, poorly drained fields should be avoided.
ALC soil wetness class	II	I	
Moisture balance (mm)	+5 [-10]	+30 [+10]	
Field capacity (days)	<210	<200	
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Excess or ill-timed N applications could lead to leaching to ground water. Shallow rooting leads to low N use efficiency, which increases risk of leaching. High agrochemical applications Risk of soil erosion due to bare soil on ridges. Mechanised harvesting rigs can cause soil damage if used on wet soils. Alternatively trampling by hand-harvest may also cause localised soil compaction.
ALC group	2	1	

Crop 16: Raspberries

Raspberries need well drained soil as even temporary waterlogging can reduce yields. A deep well-drained sandy loam with good water holding capacity is ideal. Open field grown raspberries are classified as either summer or autumn fruiting; both types are susceptible to frost damage during flowering. Wind and frost damage in the spring and autumn can lead to increased risk of fungal disease attack of flowers and fruits especially by Botrytis. As a result, low lying frost prone or windy sites should be avoided (Red Tractor Assurance, 2016j).

Typically raspberries are harvested annually, although both non-fruiting vegetative canes (primocanes) and fruiting canes (floricanes) are present. In biennial raspberries, canes grow one year and fruit the next. The floricane of all summer fruiting cultivars requires a period of chilling (c.950-1850 hours at 4°C) for them to break dormancy. The crop is usually supported on a post-and-wire system designed to carry the weight of fruits and to protect canes from excessive damage due to wind, harvesting and cultivation. Field grown raspberry canes will often require irrigation (c.25mm/week) from early flowering to the end of harvest (Creed *et al*., 2014). The crop may be protected from the weather by covering with tunnels from the onset of harvest to allow cropping to continue until late October or even mid-late November in most years.

Further manipulation of the harvest period is possible by providing summer-fruiting raspberries with all year round protection under glasshouse or polytunnels. Raspberries are grown in pots, bags or troughs containing soil-less i.e. peat or coir –based compost or other suitable substrate or planted directly into soil. Most UK supermarket production is now tunnelled. Tunnels either go on in March for early crops or pre-harvest on main season and autumn fruiters for rain protection.

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length			For biennial raspberries, shortening days and falling temperatures <15°C in late summer cause flower bud initiation, growth cessation and dormancy to set in.
Growing period (Days)	180	210	Planting: May to June Harvest: July to November the following year. (Using a variety of summer and autumn fruiting varieties).
Air or ground frost	-6		Injury to fruiting cane can occur following a sudden or prolonged cold period after mild weather. Open field grown summer fruiting varieties are susceptible to later spring frosts (late April/May). Flowers and fruit of autumn fruiting varieties can be damaged by early autumn frost in September or early October. At temperatures of ≤-6°C root damage or death may occur Frost damage can provide entry points for fungal spores, e.g. Botrytis, infection.
Other			Open field grown summer fruiting varieties are susceptible to later spring cold winds. Wind can also damage fruiting canes, leaves and roots if these are rocked by strong winds. Wind damage can provide entry points for fungal spores, e.g. Botrytis, infection.
Mean daily air temperature (°C). Optimum & [tolerable] range	17 [5]	23 [28]	

ALC accumulated temperature (day °C)	>1300		
Rainfall (mm) Optimum & [tolerable] range	800 [300]	1200 [1700]	
Site			
Aspect			Low lying frost prone sites or sites exposed to cold winds should be avoided.
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1300°C)
Gradient (°)	0	7	Steeply sloping sites where the soil surface could be prone to water erosion should also be avoided. These provide ideal conditions for the movement of *Phytophthor*a root rot from one end of a row to the other.
Soil			
Soil pH Optimum & [tolerable] range	6.0 [4.5]	6.5 [7.8]	Neutral to slightly acid pH. Soils containing a high % of free calcium carbonate are unsuitable as they are likely to cause manganese and iron deficiency, which may be difficult to correct.
Topsoil texture	S	SCL	Medium/light Sandy loam with good water holding capacity and well supplied with organic matter. Sandy soils are also ok but must have good supply of water and not be prone to erosion. Deep loams are ok but must have good drainage. Heavy clay soils are unsuitable for cane fruit production. Waterlogged soils will cause root asphyxiation and enable the rapid spread of *Phytophthora.*
Soil depth (cm)	50-150	>150	Deep
Stone content (%)	0	5	No specific limits but ALC gives limit values for Grade 1 of 5% (by volume) for stones >2 and 6 cm, in the top 25 cm of soil.
Drainage			Well drained Berries will not tolerate poor or impeded drainage[35].
ALC soil wetness class	I		
Moisture balance (mm)	+30 [+10]		
Field capacity (days)	<200		
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion.

[35] http://www.fruitgateway.co.uk/raspberry_cultivation.asp

			Where fertigation is used (i.e. nutrients applied little and often with irrigation water) soil moisture levels should not exceed field capacity as this will cause nitrate leaching. Excess or ill-timed N applications could lead to leaching to ground water. High agrochemical applications (9 spray rounds per annum[36]) lead to an associated risk of diffuse pollution. Large areas of bare soil between rows or individual plants can lead to soil erosion. Disposal of fleece crop covers. Saline conditions can develop in soil where plants are under cover.
ALC group	1	1	

[36] Garthwaite *et al.*, 2014b

Crop 17: Blackberries

As for raspberries, blackberries need well drained soil as even temporary waterlogging can reduce yields. A deep well-drained sandy loam with good water holding capacity is ideal. Blackberries flower later than summer fruiting raspberries and are not as vulnerable to frost damage. It has been estimated that blackberries require 200-1100 hours below a threshold temperature of 7°C to break dormancy (Atkinson *et al*., 2004). However, blackberries will only thrive if they have adequate shelter against prevailing winds, especially those from the north and northeast during the winter and south and southwest in the summer and autumn months. Considerable fruiting cane loss will be experienced if plants are regularly exposed to cold wind each year during the dormant and the early spring period.

The harvest period of blackberries can be extended by the use of covers over field grown crops. The production of early blackberries is also carried out by either planting into the soil, or into substrate in pots or troughs placed in the open field and covered by polythene clad 'Spanish' tunnels from late winter/early spring until the end of their harvest. Or, the plants may be grown under all year round protection. In both of these cases these crops are generally merely provided with some form of frost protection. Blackberries require far less winter chilling than raspberries so in the main the harvest of crop can be easier to manipulate (Red Tractor Assurance, 2016j).

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length	~	~	In biennial blackberries, flower bud initiation occurs in response to shortening days.
Growing period (Days)			Planting: May to June Harvest: June to November the following year. (Using a variety of summer and autumn fruiting varieties and using protection – e.g. polytunnels).
Air or ground frost	-6		Injury to fruiting cane can occur following a sudden or prolonged cold period after mild weather. Blackberries are susceptible to later spring frost and autumn frost in September or early October. At temperatures of ≤-6°C root damage or death may occur Frost damage can provide entry points for fungal spores, e.g. Botrytis, infection.
Other			Open field grown summer fruiting varieties are susceptible to later spring cold winds. Need adequate shelter against prevailing winds, from the north and northeast during the winter and south and southwest during summer and autumn (Red Tractor, 2016i). Considerable fruiting cane will be lost if plants are regularly exposed to cold wind during the dormant and early spring period. Wind damage can provide entry points for fungal spores, e.g. Botrytis, infection.
Mean daily air temperature (°C). Optimum & [tolerable] range	17 [5]	23 [28]	
ALC accumulated temperature (day °C)	>1300		

Rainfall (mm) Optimum & [tolerable] range	800 [300]	1200 [1700]	
Site			
Aspect			Low lying frost prone sites or sites exposed to cold winds should be avoided.
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1300°C)
Gradient (°)	0	7	Steeply sloping sites where the soil surface could be prone to water erosion should also be avoided. These provide ideal conditions for the movement of *Phytophthor*a root rot from one end of a row to the other.
Soil			
Soil pH Optimum & [tolerable] range	6.5	7	Neutral to slightly acid pH. Soils containing a high % of free calcium carbonate are unsuitable.
Topsoil texture	S	SCL	Sandy loam with good water holding capacity and well supplied with organic matter. Sandy soils are also ok but must have good supply of water and not be prone to erosion. Deep loams are ok but must have good drainage. Heavy clay soils are unsuitable for cane fruit production.
Soil depth (cm)	50-150	>150	Deep
Stone content (%)	0	5	No specific limits but ALC gives limit values for Grade 1 of 5% (by volume) for stones >2 and 6 cm, in the top 25 cm of soil.
Drainage			Intolerant of sites with a risk of prolonged waterlogging during the spring and autumn months. Berries will not tolerate poor or impeded drainage.
ALC soil wetness class	I		
Moisture balance (mm)	+30 [+10]		
Field capacity (days)	<200		
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Where fertigation is used (i.e. nutrients applied little and often with irrigation water) soil moisture levels should not exceed field capacity as this will cause nitrate leaching. Excess or ill-timed N applications could lead to leaching to ground water. High agrochemical applications (8 spray rounds per annum[36]) lead to an associated risk of diffuse pollution. Large areas of bare soil between rows or individual plants can lead to soil erosion. Disposal of fleece crop covers.

			Saline conditions can develop in soil where plants are under cover.
ALC group	1	1	

Crop 18: Blackcurrants

The initial siting of the blackcurrant plantation is important as flowers are easily damaged by spring frosts. Sites should have sufficient slope to drain cold air and should be situated to protect the crops from strong winds during spring and summer that can damage the bushes and strip flowers or fruit. A site can be established near to existing woodland or hedges to provide shelter or a multi-species windbreak can be established.

Blackcurrants generally require between 800-1600 hours of temperatures below 7°C depending on cultivar before buds will break in the spring (Barney and Hummer, 2005 cited by Brennan, undated). Lack of chilling results in uneven bud break and poor eventual fruit quality at harvest, although if a cultivar has a low chilling requirement there is an increased risk of frost damage due to early bud break (Brennan, undated).

Blackcurrants are generally harvested into bins and either processed or frozen within 24 hours. Within the UK, over 90% of the blackcurrant production is used for juice[37].

Requirement	Min	Max	Notes
Climate			
Day length			Short days (<15 hours) promote floral initiation, growth cessation and the start of dormancy.
Growing period (Days)			Planting: October to March (during dormant period) Flowering: March-April Harvest: early July to late August
Air or ground frost			Some blackcurrants require a frost-free site although modern varieties have a degree of frost tolerance. Dormant plants are can withstand temperatures of -30-40°C (Brennan, undated). Flowers are susceptible to spring frost damage at temperature <8°C. Temperatures of ≤-1.9°C for > 1 hour can damage flower tissue[38]
Other			Shelter from cold winds during flowering is required to encourage a warmer microclimate and the presence of pollinating insects. To prevent Botrytis, it is important to choose a site with good air movement and circulation to prevent the build-up of moist air (Red Tractor Assurance, 2016k).
Mean daily air temperature (°C). Optimum & [tolerable] range	17 [5]	25 [30][39]	Increased risk of infection of leaf spot and Botrytis in wet and warm conditions. Risk of powdery mildew increases with higher temperatures up to 25°C then is reduced.
ALC accumulated temperature (day °C)	>1300		
Rainfall (mm) Optimum & [tolerable] range	700 [500]	900[39] [1100]	
Site			

[37] http://www.fruitgateway.co.uk/blackcurrant_cultivation.asp#refs

[38] http://www.blackcurrantfoundation.co.uk/growing-blackcurrants/growing/growing-blackcurrants-commercial-markets

[39] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=9282

Aspect			Sheltered from strong winds during spring and summer.
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1300°C)
Gradient (°)	0	7	Sloping site with no obstructions to encourage air drainage.
Soil			
Soil pH Optimum & [tolerable] range	6.5 [6]	7.0 [8]	At pH >7 micronutrient deficiency is possible.
Topsoil texture	LS	SCL	Medium A variety of types are suitable. Pure sands are unsuitable due to low water availability. Heavy clays are unsuitable due to potential compaction, poor aeration and waterlogging.
Soil depth (cm)	50-150	>150	Blackcurrants produce both surface and deep roots
Stone content (%)	0	5	No specific limits but ALC gives limit values for Grade 1 of 5% (by volume) for stones >2 and 6 cm, in the top 25 cm of soil.
Drainage			Well drained. Irrigation may be required during periods of low available water capacity but should be kept to a minimum to avoid the spread of Botrytis.
ALC soil wetness class	I		
Moisture balance (mm)	+30 [+10]		
Field capacity (days)	<200		
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may be used when soil moisture is low and to give frost protection during flowering. Irrigation may increase the risk of run-off and/or soil erosion. Excess or ill-timed N applications could lead to leaching to ground water. High agrochemical applications (5-10 spray rounds per annum[40]) lead to an associated risk of diffuse pollution. Large areas of bare soil between rows or individual plants can lead to soil erosion. However, many growers plant grass or clover mixes in between rows of bushes. Disposal of polythene mulches.
ALC group	1	1	

[40] Garthwaite *et al.,* 2014b; five for 'fresh' and ten for 'processing' blackcurrants

Crop 19: Salad (field grown lettuce)

The UK climate is suitable for lettuce production due to the relatively even mild temperatures. Lettuces grow best between 12 and 18°C and are often grown near the coast where temperature fluctuations are minimised[41].

The main types of lettuce grown in the field are Romaine, Cos, Iceberg, Little Gem and continental/speciality lettuces such as Lollo Bionda, Lollo Rossa, Batavia and Red or Green Oak Leaf.

Field grown lettuce can be grown on a variety of soil types, although heavy soils are best avoided. In addition, Iceberg lettuce should not be grown on light soils, which require a water retentive soil. Lettuce is grown in glasshouse under temperature controlled conditions prior to planting in the field from February onwards, with the earliest crops covered by fleece or polythene (Red Tractor Assurance, 2016l).

Irrigation is essential for optimum crop production and conditions should be near to field capacity at planting. However, over-watering near to harvest (within 7 days) can cause problems with leaf condition and poor shelf life. Trickle irrigation is preferred to avoid soil splash from sprinkler irrigation (CALU, 2006).

Requirement	Min	Max	Notes
Climate			
Day length	~	~	Long days (>14 hours) induce flowering in combination with high temperatures (>21°C).
Growing period (Days)			Planted in February/March with subsequent plantings every 10-14 days. Early crops planted in February/March are normally covered with fleece or polythene to protect them from frost.
Air or ground frost	-1	0	Low tolerance to frost at all stages. Avoid frost pockets and exposed sites Select areas where the risk of frost is low (i.e. coastal).
Other			Wind can help reduce pests and diseases by ensuring that the crop environment is not sufficiently humid for fungal development. However, lettuce is easily damaged by strong winds.
Mean daily air temperature (°C). Optimum & [tolerable] range	12 [5]	18 [30][42]	
ALC accumulated temperature (day °C)	>1300		
Rainfall (mm) Optimum & [tolerable] range	1100 [900]	1350 [1600][42]	
Site			
Aspect	~	~	
Altitude (m)			Land at high altitude will be unsuited due to factors such as accessibility, soil wetness and temperature (i.e. AT0 <1300°C)

[41] http://www.britishleafysalads.co.uk/plough/plough-plate.shtml

[42] http://ecocrop.fao.org/ecocrop/srv/en/dataSheet?id=1313

Gradient (°)	0	7	Limitations for planting and harvesting machinery. 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	6.5 [4.5]	7 [7.5]	Lettuce crop is sensitive to acidity.
Topsoil texture	S	ZL	Medium to light soil type.
Depth (cm)	20	50	Shallow soil is acceptable.
Stone content (%)	0	5	No specific limits but ALC gives limit values for Grade 1 of 5% (by volume) for stones >2 and 6 cm, in the top 25 cm of soil.
Drainage			Well drained
ALC soil wetness class	I		
Moisture balance (mm)	+30 [+10]		
Field capacity (days)	<200		
Other			
Environmental risks			High levels of local water abstraction where crop is irrigated. Irrigation may increase the risk of run-off and/or soil erosion. Excess or ill-timed N applications could lead to leaching to ground water. In addition, lettuce accumulate nitrate in their leaves; limit values have been set of between 2000-5000 mg NO_3/kg (depending on type). Shallow rooting leads to low N use efficiency, which increases risk of leaching. Agrochemical applications lead to an associated risk of diffuse pollution. Disposal of fleece or polythene crop covers. Frequent trafficking due to successional harvesting/planting.
ALC group	1	1	

Crop 20: Grapes (cool-climate cultivars - Pinot noir, Pinot Meunier, Gewürztraminer)

In 2015, there was an estimated 40 ha of commercial vineyards in Wales and *c*.1840 across the UK. The main varieties grown in the UK are Chardonnay (28%), Pinot noir (26%), Bacchus (9%) and Pinot Meunier (7%) varieties (FSA, 2015)[43].

Grape vines (*Vitis vinifera*) are generally planted assuming a lifespan of >35 years (Ashenfelter and Storchmann 2014). The growth cycle begins with bud-break in March/April, continues with flowering in May/June, berry growth and colouring in July/August, maturation in September/October, and culminates with leaf fall in autumn, followed by winter dormancy (Gladstones 1992 cited by Nesbitt, 2016). Neither photoperiod nor vernalisation is very relevant for flowering induction (Vasconcelos *et al*., 2009).

Temperature is considered the key factor in viticulture viability and wine quality (Jones *et al*. 2005) and generally viticulture is deemed suitable within areas that have a growing season (April to October) average temperature of 12–22°C (Jones 2007). Although some cultivars can tolerate minimum winter (dormant period) temperatures of as low as -20°C (Davenport *et al*. 2008), spring air frosts that injure developing shoots and buds, and frosts after budburst can reduce yield. Spring air frosts can pose a significant economic risk to vineyards as, as the perennial nature of grape vines leads to crop loss in both the present and following year of production (Trought *et al*. 1999). Windy conditions can disrupt flowering, lower vineyard temperatures (Jones and Davis 2000) and impact vine canopy structures causing shading and reduced photosynthesis. Conversely breezes are regarded as beneficial in providing air movement and reducing disease instance (Skelton, 2014 cited by Nesbitt, 2016).

Well-drained soils are essential (CALU, 2007d), to promote soil warming in spring (temperature affects the size and function of the root system) and induce lower levels of humidity, which reduces the risk of mildews and other disease pressures (Lanyon *et al*. 2004; Davenport & Stevens 2006).

Requirement	**Min**	**Max**	**Notes**
Climate			
Day length			Day length does not influence flower induction, high temperature and light are the main drivers. Light requirements are high during the growing season (5.5-6.5 hours of sunshine per day.
Growing period (Days)	210	240	Vines have a long life-span (> 30 years). Annual growth cycle: bud break (March/April) to maturation in September/October. Dormancy: November to February.
Air or ground frost			Moderately susceptible Avoid frost hollows Air frost in April and May when buds are bursting and shoot emerging (Trought *et al*., 1999) is the most damaging.
Other			Shelter from prevailing strong winds which can disrupt flowering and lower vineyard temperatures.
Mean daily air temperature (°C). Optimum & [tolerable] range	12 [10]	22[44] [30]	For the growing season of April to October. Pinot Gris, Gewurztraminer (13-15°C) and Pinot Noir (14-17°C) are grape varieties that can ripen at lower average growing season temperatures (Nesbitt, 2016).
ALC Accumulated temperature	1000	>1300	

[43] https://www.food.gov.uk/business-industry/winestandards/ukvineyards

[44] Jones, 2007.

(day °C)			
Rainfall (mm) Optimum & [tolerable] range	700 [400]	850 [1200]	450->550 mm Some summer rainfall is needed. June rainfall is an important determinant to wine yield and values in the range of 40-50 mm have been associated with high yield (Nesbitt, 2014).
Site			
Aspect			South facing slopes have greater direct solar radiation inception (Nesbitt, 2014).
Altitude (m) Optimum & [tolerable] range	25	80[45] [150]	Elevation suitability for viticulture is restricted by decreasing temperatures at higher altitudes and a greater potential for wind exposure where surrounding terrain does not afford shelter (Gladstones, 1992 cited by Nesbitt, 2016).
Gradient (°) Optimum & [tolerable] range	3 [1]	9 [20]	The optimum is a gentle slope. 5-15% [3-9°] (Jones, 2004). However, in practice, vines are often grown on moderate slopes. The potential for mechanical vineyard management is limited on slopes above 10% [6°]. On flat sites, there is an increased risk of cold air accumulation and potential frost damage.
Soil			
Soil pH Optimum & [tolerable] range	5.5 [4.5]	8.0 [8.5]	It is generally accepted that soil pH should be between 5.5–8.0 for optimum vine growth and soil microbial composition (e.g. Proffitt and Campbell-Clause, 2012).
Topsoil texture	SL	SCL	Medium Deep and well drained. Clay soils are not suitable.
Depth (cm)	20-50	>150	Deep
Stone content (%)			No limit on stoniness
Drainage			Well drained
ALC soil wetness class	III	I	Wetness Class III on S, LS, SL, SZL, Zl, MZCL, MCL and SCL only. For other soil types Wetness Class II is limit.
Moisture balance (mm)	-50 [-55]	+30 [+10]	
Field capacity (days)	<230	<200	
Other			
Environmental risks			Excess or ill-timed N applications could lead to leaching to ground water. Agrochemical applications lead to an associated risk of diffuse pollution. Soil erosion and run-off due to bare soil and lack of leaves on vines from late autumn to spring.
ALC group	3b	1	

Crop 21: Daffodils

Daffodils can be grown for cut flower or bulb production, although many growers operate a combined system. Daffodils are planted in raised ridges similar to potatoes and many growers operate on a two

[45] Skelton, 2014 cited by Nesbitt, 2016

or three year system. Bulbs are planted in year 1, followed by flower harvests in year 1, 2 or 3, before bulbs are lifted in year 2 or 3.

Galanthamine is a long acting, selective and reversible acetylcholinesterase inhibitor that has been a licensed treatment for Alzheimer's disease since 2000. The main source of galanthamine is the alkaloid galanthamine extracted from plants including *Narcissus* (daffodil) spp. Production of galanthamine has also been shown to increase in response to plant stress and it has been reported that Narcissus grown at higher altitude, such as upland areas of Wales, may have more galanthamine than those grown at lower levels (Morris *et al*., 2006). However, recent research (Fraser *et al*., 2017), where daffodils were sown into upland pasture, did not show an effect of altitude on galanthamine concentrations. Instead high levels of plant competition were proposed to increase galanthamine. The galanthamine was obtained from cut green material so that a single planting of bulbs could potentially produce multiple harvests. There is potential to develop this market once further research has been completed.

Requirements	**Min**	**Max**	**Notes**
Climate			
Day length	~	~	Flowering is controlled by the duration of warm and cool periods.
Growing period			Plant September and harvest flowers in February to March. Bulbs remain in soil for 2-3 years.
Air or ground frost			Most daffodils are hardy to -32°C
Other	~	~	
Mean daily air temperature (°C). Optimum & [tolerable] range			Cold temperatures in winter trigger the biochemical processes which start flowering.
Rainfall (mm) Optimum & [tolerable] range			
Site			
Aspect	~	~	
Altitude (m) Optimum & [tolerable] range			Land at high altitude may be unsuited due to factors such as accessibility, soil wetness and temperature.
Gradient (°) Optimum & [tolerable] range	0	11	Limitations for planting and harvesting machinery. 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. 11° is the ALC limit for grade 3b land.
Soil			
Soil pH Optimum & [tolerable] range	6	7	
Topsoil texture	S	SCL	Moisture retentive but well drained.
Depth (cm)	50	>50	
Stone content (%)			No specific limits but ALC gives limit values for Grade 3b of 35% and 20% (by volume) for stones >2 and 6 cm, respectively in the top 25 cm of soil.
Drainage			Well drained Daffodils have a high requirement for water whilst growing

ALC soil wetness class	III	I	Wetness Class III on S, LS, SL, SZL, Zl, MZCL, MCL and SCL only. For other soil types Wetness Class II is limit.
Moisture balance (mm)	-50 [-55]	+30 [+10]	
Field capacity (days)	<230	<200	
Other			
Environmental risks			Nitrate leaching on light soils due to high application rates and inefficient plant uptake. Diffuse pollution from agrochemical applications.
ALC group	3b	1	

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Appendix 1. Soil types

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	