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ALC Technical Review
Part 4: Soil wetness

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Glossary

AAR: Average Annual Rainfall. AAR is a measure of the total amount of rainfall, falling in a calendar year (observation period 1941-1970). This is different to the duration of wetness throughout a calendar year – see FCD.

ALC: Agricultural Land Classification system. This is a robust, scientific system to assess agricultural land quality at a range of mapping scales. The ALC is the only approved system for grading land quality in England and Wales. (See also BMV)

ASR: Average Summer Rainfall (April to September, measured in millimetres). ASR measures rainfall at the critical time of year for crop growth (observation period 1941-1970). This is not used as a standalone criterion but is implicit in some background calculations.

AT0: Median Accumulated Temperature above 0°C (January to June). This measures the warmth of an area during a period critical for germination and plant growth. AT0 is simply a sum of all temperatures above 0°C, summed daily from January to June. This is used in the assessment of overall climate. April to September values of AT0 is used in some background calculations (this is known as ATS, see below).

ATS: Median Accumulated Temperature above 0°C (April to September). ATS is a sum of all temperatures above 0°C, summed daily from April to September.

BMV: Best and Most Versatile land. BMV land is ALC Grade 1, Grade 2 and Sub-grade 3a of the ALC system. BMV land is afforded protection through national planning policy; this policy is different in England and Wales. In Wales, policy states that 'considerable weight should be given to protecting such land from development' whereas in England planning should recognise the 'economic and other benefits' of BMV land and 'where significant development of agricultural land is demonstrated to be necessary, areas of poorer quality land should be preferred to those of a higher quality'.

FCD: Field Capacity Days. FCD is the number of days per year a soil is at Field Capacity. Field Capacity (FC) is maximum water soil content under gravity, i.e. the soil moisture deficit is 0 and the point at which drainage starts. At Field Capacity, soils are considered too wet for cultivation. FCD is a key criterion in ALC assessment of soil wetness and workability.

Hydraulic conductivity (K): Is the ability of water to flow through soil in response to a hydraulic gradient. See also saturated hydraulic conductivity.

Interactive limitations. In ALC, these are physical limitations which result from interactions between climate, site and soil. The interactive limitations in ALC are soil wetness, droughtiness and erosion. Interactive limitations allow for similar soils to be assessed differently, in wetter or drier parts of England and Wales. See also Standalone limitations.

LCA: Land Capability Assessment for Scotland. This is the land classification system used in Scotland which is very similar to ALC but differs in several aspects. The LCA uses 7 classes and has greater subdivision of grassland/moorland areas than ALC.

Liebig's law of the minimum. If a combination of limiting factors exists, *only* the one most limiting determines the overall severity of limitation. This term is used in EC documents and is synonymous with 'most limiting factor' in ALC. (See most limiting factor)

MAFF: MAFF was the Ministry of Agriculture, Fisheries and Food (now DEFRA).

MAFF 1988 Guidelines/the Blue Book. *The Revised guidelines and criteria for grading the quality of agricultural land (MAFF 1988).* This is the extant and only approved system for grading land quality in England and Wales. The guidelines came into force on 1 January 1989 superseding any previous ALC surveys or guidelines (see MAFF Technical Reports: Tech 11 and 11/1)

MORECS: Met Office Rainfall and Evaporation Calculation System. Provides estimates of evaporation and soil moisture deficit for the UK. It is run each week and produces daily information for a range of crop types and soil properties.

Mineral soils: Mineral soils are soils which are not organic-mineral soil or peaty and have less than 6-10% organic matter. Most lowland arable soils outside Fenland are mineral. See Appendix 2 of the MAFF 1988 Guidelines for definitions.

Most limiting factor (ALC). If a combination of limiting factors exists, the most limiting one only is used to determine severity of limitation and hence ALC Grade. See Liebig's law of the minimum.

Organic-mineral or peaty soils. Organic mineral soils have between 6-25% organic matter, depending on clay content. Peaty soils have 20-100% organic matter, depending on clay content. See Appendix 2 of the MAFF 1988 Guidelines for definitions.

Predictive ALC: The Predictive ALC was introduced in Wales in 2017. It is a web-based model refining ALC grading at an all Wales level. It uses background climate and terrain models, linked to NATMAP soil property data. It then calibrates the data to the ALC system. Predictive ALC Grades (Including Subgrade 3a and 3b) can be viewed, along with all Post Revision field surveys. The Predictive ALC has superseded the Provisional ALC maps in Wales and is available on the Welsh Government website. It is the primary source of strategic ALC information in Wales. (See Provisional ALC).

http://lle.gov.wales/catalogue/item/PredictiveAgriculturalLandClassificationALCMap2/?lang=en

Provisional ALC maps: Maps prepared between 1968 and 1974, classifying all of England and Wales into 5 Grades. The maps were intended as a strategic guide to agricultural land quality. Originally produced at a scale of one inch to the mile (1:63 360) but subsequently generalised to a scale of 1:250 000. The maps series should only be used for a strategic guide to land quality and not relied on for site specific assessments. For a definitive grading, a survey according to the MAFF 1988 guidelines is needed.

The Provisional ALC maps were replaced in Wales by the Predictive ALC in 2017, which is available on the Welsh Government website. (See Predictive ALC).
http://lle.gov.wales/catalogue/item/PredictiveAgriculturalLandClassificationALCMap2/?lang=en

Saturated hydraulic conductivity (K_{sat}): A quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient.

Soil structure: Soil structure is the aggregation of individual soil particles into discrete units, called peds or structural units. These can be classified into different shapes, sizes etc. Differences between soil structural type and condition can have a large effect on soil water movement. Soil structure is important for soil wetness/workability and droughtiness assessment.

Soil texture: Soil texture is defined according to the relative proportions of sand, silt and clay fractions.

Standalone limitations: In ALC, these are limitations directly affecting grade independent of soil/climate interactions – e.g. flooding, gradient, topsoil stone content and overall climate.

SWC: Soil Wetness Class. SWC is the key descriptor for the severity of soil wetness. SWC measures the amount of the year a soil is wet above certain depths on a scale of I – VI. SWC I is driest, SWC VI is wettest. SWC I to IV are most encountered in ALC. For ALC, SWC is assessed using (a) depth to gleyed horizon and depth to slowly permeable layer – measuring how quickly water can move through a soil profile– and (b) the number of Field Capacity Days (FCD) – measuring the duration of climatic wetness. See Appendix 3 of the MAFF 1988 guidelines for a full definition. (See also Wet).

Wet: In soil wetness class assessment, 'wet' means water films are visible on the surfaces of grains or peds. Excavation below a wet horizon will cause water to flow down the exposed face, though flow may be very slow and confined to major pores and fissures. For a full definition see Soil Survey Field Handbook (Hodgson J.M. 1997 – definition as Hodgson J.M. 1976).

1 Introduction

- The Agricultural Land Classification in England and Wales (ALC) provides a framework for classifying agricultural land according to the extent to which its physical or chemical characteristics restrict agricultural use. The limitations may affect the range of crops which can be grown, the level and consistency of yield and the associated cost of farming the land. The ALC grade describes the capability of the land for a range of potentially suitable crops.
- The ALC was originally devised and introduced in the 1960s and it provided a framework for classifying land into five classes (ALC grades 1-5) according to the extent that climatic, soil and site characteristics limited agricultural production. Following a review of the system the ALC was updated in the 1970s to divide ALC grade 3 land into sub-grades 3a, 3b and 3c. Subsequently, the system was further updated in the 1980s following extensive review and testing, when it was decided that there was no longer the need for a three-fold sub-division of Grade 3 land and the Grade 3c was removed. In addition, the criteria used to assess climatic limitations and climate-soil interactions were updated based on the best and most up to date information available at the time.
- Land is still graded in accordance with the guidelines and criteria established in 1988 (MAFF, 1988). Given that the guidelines were published over 30 years ago, it is possible that the threshold limits for establishing grading for some factors are no longer valid. In addition, major advances in technology since 1988 may provide methods for assessing criteria that were not previously possible (e.g. GIS or remote sensing). The ALC was originally developed as a field-based system, supporting planning policy to protect high quality agricultural land from loss to development. More recently, the ALC system has also been used as a modelling platform using national soil, climate and terrain datasets. This has been helpful for assessing future land capability, land suitability for specific crops, and land use planning in the wider countryside such as woodland planting risk maps. This report reviews the ALC soil wetness assessment for both (a) the original planning support and (b) more recent modelling roles. Importantly, the requirements for an ALC field assessment tool and capability/suitability modelling can be quite different.
- This report reviews the methodology and current data used in ALC to assess soil wetness. In the ALC soil wetness indicates the extent to which excess soil water imposes restrictions on crop growth and cultivations or grazing by livestock. The severity of the limitation is determined by the amount and frequency of rain in relation to evaporation, the soil water regime (depth to slowly permeable or impermeable layer) and topsoil texture.
- The report builds on earlier work which reviewed the evidence base for ALC climate, site and soil limitations (Rollett and Williams, 2019, SPEP2018-19/12; Rollett and Williams, 2020, SPEP2019-20/04; Rollett and Williams, 2021, SPEP2020-21/12).

2 Objectives

- To review the ALC wetness and workability assessment to determine if it is still fit for purpose and to provide a foundation for any future revisions to ALC guidance. The review is intended to assess and discuss issues and not to produce a revised soil wetness and workability method for ALC. This report has:
  - Reviewed the climate reference data currently used in the ALC soil wetness and workability assessments

- Reviewed the methods used in the ALC soil wetness and workability assessment methods; also, the assumptions that underlie these methods.
- Reviewed other existing methods for assessing soil wetness and workability in agricultural situations.
- Summarised the strengths and weaknesses of the ALC and made recommendations for future work and/or potential updates to ALC methodology.

3 The Agricultural Land Classification

- The principal physical factors influencing agricultural production are climate, site (e.g. gradient or microrelief) and soil. These factors, together with interactions between them, form the basis for classifying land into one of six grades; Grade 1: excellent quality to Grade 5: poor quality. Grade 3 is further divided into two sub-grades designated 3a and 3b (MAFF, 1988)[1]. The top three grades (1-3a) are defined by Section 3.58 of Edition 11 of Planning Policy Wales (Welsh Government, 2021) and the National Planning Policy Framework for England (Ministry of Housing, Communities & Local Government, 2021) as the 'best and most versatile' (BMV) agricultural land and are suitable for growing 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 and soil chemical properties. The final ALC grade given to a location is the lowest grade from any of the criteria (i.e. criteria are combined according to the agronomic law of the minimum, Liebig's law).
- Certain criteria (i.e. soil droughtiness, soil wetness and workability, gradient, topsoil stone content and soil depth) have bespoke, in field, assessment methods to directly arrive at an ALC grade. Flooding is similar but depends on third party data that is often not easily available. Other criteria (i.e. micro-relief, chemical, erosion, frost, aspect, exposure and irrigation)[2] are considered in the ALC Guidelines. However, these are on a case-by-case basis with no specific threshold values to directly arrive at an ALC grade.
- In Wales, Grade 1 land is located in small pockets of lowland North East and South Wales (Figure 1[3]) and in England, around The Wash, the Vale of York, North Kent and on the North West coast near Ormskirk (Figure 2). Similarly, Grade 2 land is mainly located in lowland North and South Wales, Anglesey and Pembrokeshire and in Eastern England. Grade 3 land is more widely distributed and is in low lying coastal and inland areas of Wales, river valleys (e.g. the Wye and Severn) and along the Welsh/English border; in England Grade 3 land predominates. Grade 4 and 5 agricultural land is concentrated in the central upland areas of Wales and the north/northeast uplands of England. Only agricultural land of Grade 3b and above will typically be suited to arable crops (MAFF, 1988). However, light Grade 4 land may be cropped in the East and Southeast of England although yields are likely to be limited.

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[1] http://publications.naturalengland.org.uk/file/5526580165083136
[2] Although irrigation is included in the 1988 ALC guideline the 1997 changes to national planning guidance removed the potential to upgrade land where irrigation was available, and it is no longer used as a factor in grading land.
[3] Note that although both Figures 1 and 2 illustrate the location of ALC land by grade in Wales and England, respectively, they are not strictly comparable. Figure 1, the predictive ALC map for Wales was introduced in 2017, it is a web-based model which uses the best available information to predict the ALC grade of land. Figure 2 shows the provisional grades for England based on maps prepared between 1967 and 1974; the maps provide a strategic guide to land quality rather than site specific guidance.

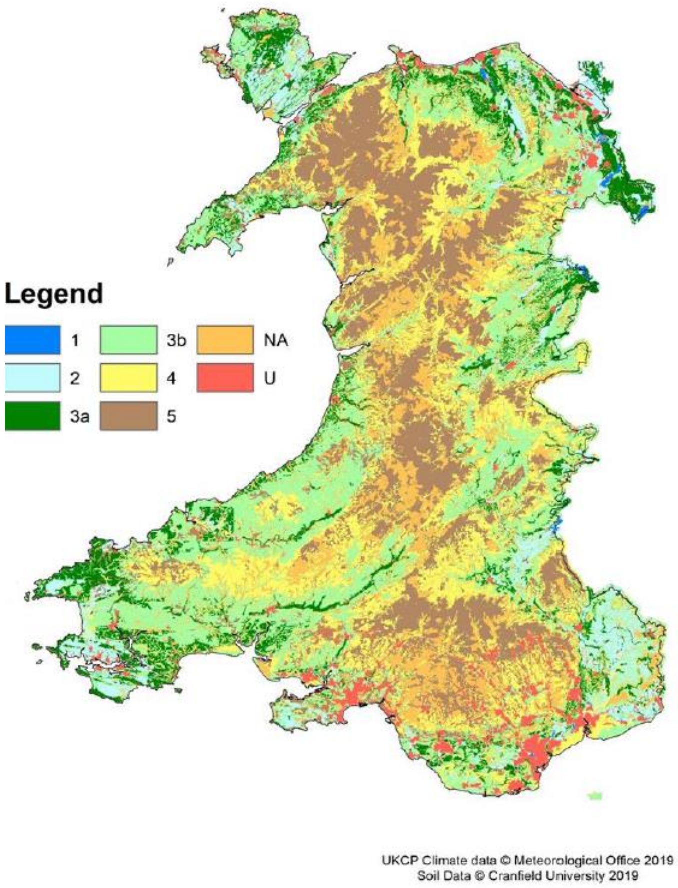

Figure 1. Predictive agricultural land classification (ALC) map for Wales (Source: Keay and Hannam, 2020).

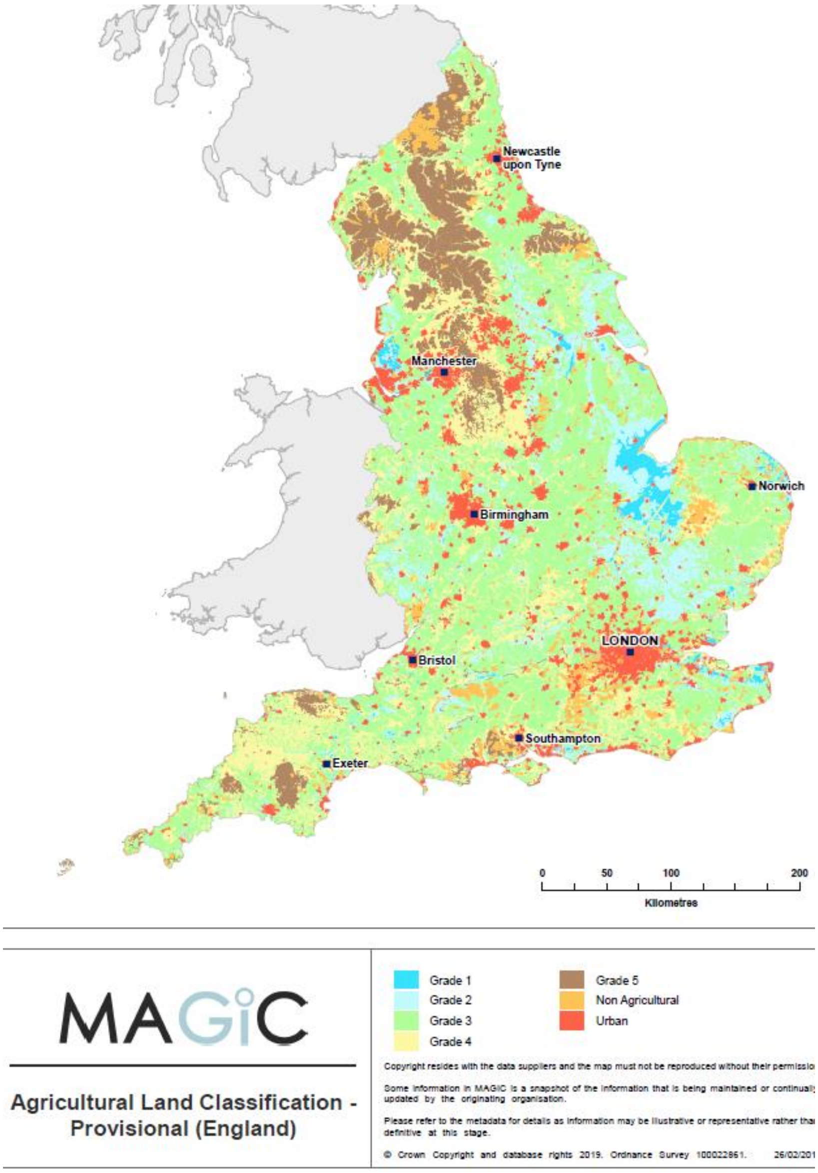

Figure 2. Agricultural land classification (ALC) for England.

3.1 ALC 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 moisture, soil aeration, the number of field capacity days (i.e. when soils are wet enough for drainage to occur) and the ease of access to land to carry out field operations or for grazing by livestock (livestock are typically housed for longer when the climate is wetter/cooler to avoid damaging the soil/sward and for animal health/welfare).
- In climatic terms for ALC, 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). The main climatic factors currently considered in the ALC are temperature (accumulated temperature January to June-AT0) and rainfall (average annual rainfall-AAR), although account is also taken of local factors such as exposure, aspect and frost risk. Local factors (where relevant) are assessed on a case-by-case basis. Climatic criteria are considered first when classifying land as severe limitations will restrict land to low grades irrespective of favourable soil or site conditions.
- The physical limitations which arise from interactions between climate, site and soil are soil wetness, droughtiness and erosion. Soil droughtiness indicates the degree to which a shortage of soil water influences the range of crops which can be grown and the level and consistency of yield which may be achieved. In comparison, a soil wetness limitation exists where excess soil water limits plant growth or imposes restrictions on cultivations or grazing by livestock. The limitations are not mutually exclusive in that some soils can be wet in winter but droughty in summer.

4 ALC climatic datasets

- The climatological data underpinning the ALC system and the origin and methodology for deriving it is described in the 1989 Meteorological Office publication: ‘Climatological Data for Agricultural Land Classification’, which was prepared in association with MAFF and the Soil Survey and Land Research Centre (SSLRC). The dataset comprises location, altitude, rainfall, temperature, soil moisture deficit and duration of field capacity datasets with a 5 km grid spacing.
- Climatic data are used in ALC for the assessment of the climate, droughtiness and wetness limitations. To provide consistency in those assessments a standard data source was required for the calibration and operation of the system. Grid point datasets with a spacing of 5 km were assigned to the whole of England and Wales and standard methods were devised for estimating the value of each parameter at any location. The grid is coincident with the 5 km intervals of the Ordnance Survey National Grid, having its origin south-west of the Scilly Isles (Figure 3.).

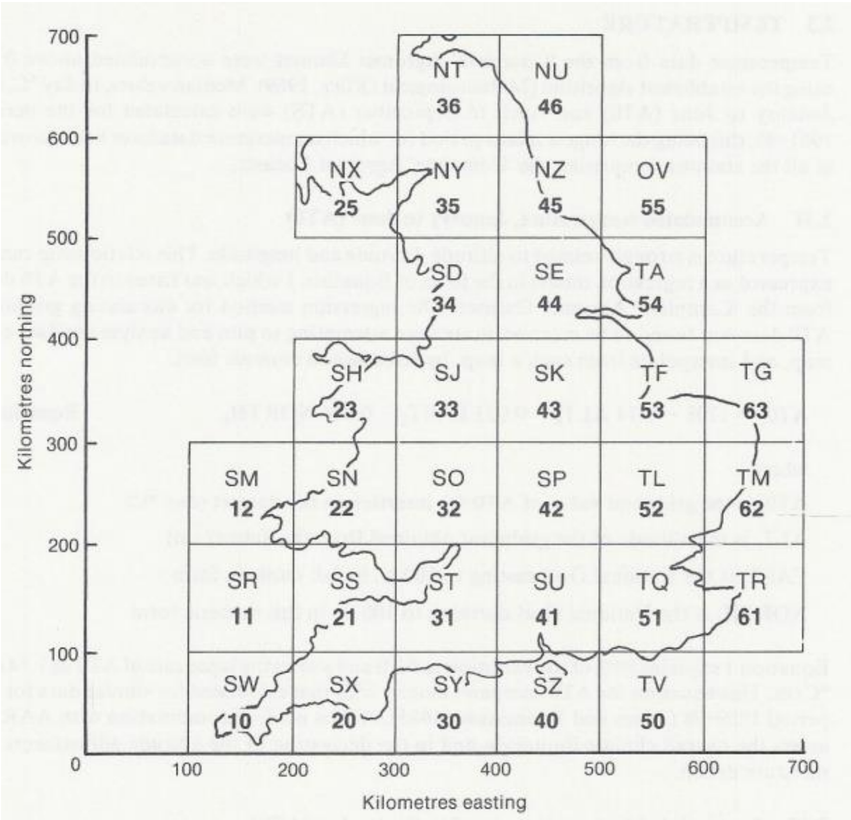

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Figure 3. The lettering and numbering of the 100 km squares of the National Grid (Source: Meteorological Office, 1989).

- The ALC datasets are held in LandIS[4], a computer-based land information system which was developed by the SSLRC and funded by MAFF. LandIS can be used to obtain both grid point and interpolated values for specified grid references. The complete dataset was also published by the Meteorological Office in 1989 and the procedure for obtaining interpolated values is explained in that publication: "Climatological data for agricultural land classification"[5].
- LandIS digital datasets are maintained by Cranfield University and access to soil data is governed by an agreement between Cranfield and Defra. Typically, there is a charge to use the data; the standard minimum charge is around £600 + VAT for a digital dataset (£225 royalty fees + £375 preparation and administration)[6]. In contrast, the ALC climatological dataset is freely available on the Natural England website to download.
- The five agroclimatic parameters used in the ALC system (average annual rainfall, average summer rainfall, median duration of field capacity, median accumulated temperature >0°C, January to June and median accumulated temperature >0°C, April to September) and the associated limitation factors are listed in Table 1. The field capacity dataset was compiled by the SSLRC based on Meteorological Office data. The other datasets were compiled by the Meteorological Office and processed by the SSLRC prior to their incorporation in LandIS. Datasets of altitude and average annual rainfall change with altitude (i.e. lapse rate of AAR) are also held on LandIS for use in the interpolation from grid point values to site values.

[4] https://www.cranfield.ac.uk/themes/environment-and-agrifood/landis
[5] http://publications.naturalengland.org.uk/publication/6493605842649088
[6] http://www.landis.org.uk/data/datapricing.cfm

Table 1. Agroclimatic parameters used in the ALC system. Source (Meteorological Office, 1989)

Limitation Factor	Parameter	Observation period
Climate	Average annual rainfall (AAR) Median accumulated temperature >0°C, January to June (AT0)	1941-1970 1961-1980
Soil wetness	Median duration of field capacity days (FCD)	1941-1970
Soil droughtiness	Average summer rainfall, April to September (ASR) Median accumulated temperature >0°C, April to September (ATS)	1941-1970 1961-1980

4.1 Data sources

- The influence of climate on soil wetness is assessed by reference to median field capacity days (FCDs). The spatial distribution of FCDs has been mapped by the SSLRC and is part of the grid point dataset described above. Table 2, below, shows an extract from the grid datasets which are provided for 5 km intersections of the National Grid.

4.1.1 Field capacity dataset

- Jones (1985) reports that the Soil Survey of England and Wales replaced the system of drainage classes by a system of wetness classes (describing the duration of waterlogging at specific depths in the soil) in the 1976 update of the Soil Survey Handbook. Wetness classes were defined after detailed analysis of *c*.1000 site-years of water table measurements. Robson and Thomasson (1977) noted that the most important factor affecting waterlogging was the duration of the period when rainfall exceeded evaporation. As a result, it was decided to examine the possibility of using an estimation of the duration of field capacity, in addition to soil permeability and morphological evidence for gleying, as a means of estimating the wetness class of soils where direct water table measurements where available (Jones, 1985).

- In the ALC, the duration of field capacity is a meteorological parameter which estimates the period when the soil moisture deficit is zero. Soils usually return to field capacity during the autumn or early winter period and the field capacity period, measured in days, ends in the spring when evapotranspiration exceeds rainfall, and a moisture deficit begins to accumulate (Met Office, 1989). Smith and Trafford (1976) described a method for estimating the average period of meteorological field capacity from monthly water balances of rainfall and evapotranspiration for the period 1941-70. They listed median dates for the return to and end of field capacity for 52 MAFF agroclimatic areas along with a range of values for differing annual rainfall totals. These dates were regressed on AAR (for 1941-70) by the SSLRC to generate a 10 km grid dataset (Jones and Thomasson, 1985). This dataset has subsequently been resolved to 5 km using the grid point values of AAR described below (Ragg *et al*., 1988). Duration of field capacity is used in combination with soil characteristics to assess the soil wetness limitation.

4.1.2 Rainfall data

- The reference rainfall data for ALC is based on records from several thousand rain gauges for the year 1941-1970, which was the international standard period when the Met Office published the ALC climatological dataset. Note, however, that although there were about 6,000 stations recording rainfall in the 1941-1970 period moisture deficit data was based only on the *c*.1,000 stations that had continuous records for the period 1961-1975 (Jones and Thomasson, 1985).

- Grid point AAR values (mm) were interpolated from unpublished rainfall maps at a scale of 1:250,000, on which the published 1:625,000 map for 1941-70 was originally based (Meteorological Office, 1977). Grid point ASR values (mm) were manually interpolated from an unpublished 1:625,000 scale map of average summer rainfall for 1941-70.
- The rate at which rainfall changes with altitude (lapse rate) is used to enable grid point values of AAR to be interpolated for intermediate locations between grid points.

Table 2. Extract from ALC dataset (Source: Meteorological Office, 1989).

Key to abbreviations: SQ. Lettering for 100 km grid square; E. National grid easting (m x 10^2); National Grid northing (m x 10^2); ALT. Height above mean sea level (m); AAR. Average annual rainfall (1941-70, mm); LR. Lapse rate of AAR (mm/m); ASR. Average summer rainfall (1941-70, mm); AT0. Accumulated temperature above 0°C (median value, January to June 1961-80, day °C); ATS. Accumulated temperature above 0°C (median value, April to September 1961-80, day °C); MDW. Moisture deficit winter wheat (mm); MDP. Moisture deficit potatoes (mm); FCD. Duration of field capacity (median value 1941-70, days).

SQ	E	N	MAPREF	ALT	AAR	LR	ASR	ATO	ATS	MDW	MDP	FCD
NT	550	000	35506000	398	1546	0.7	650	908	1768	11	0	317
NT	600	000	36006000	282	1390	0.3	685	1040	1917	19	0	294
NT	600	050	36006050	290	1311	0.7	570	1028	1903	31	0	282
NT	650	000	36506000	341	1396	0.3	680	971	1842	13	0	296
NT	650	050	36506050	276	1303	0.6	590	1043	1922	30	0	281
NT	700	000	37006000	532	1290	0.8	670	752	1601	0	0	281
NT	700	050	37006050	368	1367	0.7	675	937	1806	11	0	294
NT	700	100	37006100	210	960	0.5	560	1115	2004	40	12	234
NT	750	000	37506000	330	1221	1.2	660	981	1857	17	0	272
NT	750	050	37506050	432	1196	0.9	670	863	1726	5	0	268
NT	750	100	37506100	324	1097	0.8	590	984	1861	25	0	258
NT	750	150	37506150	273	978	0.8	520	1040	1923	39	9	246
NT	750	350	37506350	46	704	0.5	360	1290	2200	87	72	182
NT	800	000	38006000	238	1050	1.0	570	1085	1975	37	7	249
NT	800	050	38006050	377	1108	0.6	640	924	1796	14	0	259
NT	800	100	38006100	446	1110	0.5	635	844	1707	7	0	261
NT	800	150	38006150	334	1071	0.5	580	969	1846	25	0	259
NT	800	200	38006200	276	1010	0.6	500	1033	1917	41	12	250
NT	800	250	38006250	185	919	0.8	415	1135	2030	63	41	234
NT	800	300	38006300	192	750	0.8	385	1124	2018	68	46	196
NT	800	350	38006350	107	718	0.5	365	1219	2124	80	62	186
NT	800	400	38006400	45	640	0.6	345	1288	2200	90	76	171
NT	850	000	38506000	297	974	0.7	540	1017	1902	35	4	241
NT	850	050	38506050	343	1061	0.4	600	962	1841	22	0	257
NT	850	100	38506100	419	1017	0.3	550	873	1742	20	0	250
NT	850	150	38506150	552	1077	0.3	630	719	1571	0	0	258
NT	850	200	38506200	267	1034	0.4	540	1042	1929	37	7	253
NT	850	250	38506250	295	997	0.5	475	1008	1892	43	14	249
NT	850	300	38506300	214	829	0.5	400	1098	1991	63	39	211
NT	850	350	38506350	95	702	0.4	365	1232	2140	81	64	182
NT	850	400	38506400	15	629	0.7	340	1321	2239	94	81	171
NT	850	450	38506450	54	692	1.0	340	1274	2187	90	75	181

4.1.3 Temperature data

- The AT0 dataset for the ALC is based on temperature data from the 94 stations in the Complete Agromet Database (Field, 1983), which had complete records over the period 1961-1980. Accumulated temperatures for the period January to June each year were computed for each station from daily measurements of maximum and minimum temperature and the median value of AT0 in the period 1961-80 was determined. The median values were then extrapolated to grid points by means of a regression equation which related accumulated temperature, altitude, latitude (National Grid northing) and longitude (National Grid easting). The following equation which explains approximately 90% of the variation in AT0 for the 94 agrometeorological recording stations, was used:

- ATO (day degrees Celsius) = 1708 -1.14A -0.023E -0.044N

  A is altitude above mean sea level (metres)

  E is National Grid easting to 100 m (four significant figures)

  N is National Grid northing to 100 m (four significant figures)

- The equation shows the lapse rate of AT0 as 1.14 day °C/m.
- The ATS dataset (1961-80) was created directly from the AT0 dataset using the following linear regression, which explains more than 90% of the variation in ATS for the 94 stations:
  - ATS (day degrees Celsius) = 611 + 1.11AT0 + 0.042E

    AT0 is the grid point AT0 value

    E is the National Grid easting to 100 m (four significant figures)

4.2 Interpolation from grid points

- For sites not located precisely at a 5 km grid point standard routines are available in LandIS to calculate the value of any climatic parameter by interpolation from adjacent grid point values. The routines adjust for height differences between the site and up to four adjacent grid points, using the appropriate lapse rate or altitude correction factor, and then interpolate by calculating a distance weighted mean. Where a site falls exactly on an easting or northing which passes through two grid points the interpolation uses only those two grid point values. Interpolated values do not take account of microclimatic factors. The methodology for interpolation is described below and although complicated can be calculated manually:
- The adjustment to FCD is:
  - $FCD_a = FCD_g + 0.1446\ [(LR\_AAR_g\ (ALT_s - ALT_g)]]$

    FCD_a is the altitude adjusted grid point value of FCD (day)

    FCD_g is the grid point value of AT0 from the dataset (day)

    LR_AAR_g is the grid point value for the lapse rate of AAR from the dataset (mm/m)

    ALT_s is the altitude of the site (m)

    ALT_g is the altitude of the grid point from the dataset (m)

    Where FCD_a >365, FCD is taken to be 365

- The adjustment to AAR is
  - $AAR_a = AAR_g + LR\_AAR_g(ALT_s - ALT_g)$

    AAR_a is the altitude adjusted grid point value of AAR (mm)

    AAR_g is the grid point value of AAR from the dataset (mm)

    LR_AAR_g is the grid point value for the lapse rate of AAR from the dataset (mm/m)

    ALT_s is the altitude of the site (m)

ALT_g is the altitude of the grid point from the dataset.

- And to adjust AT0 it is:
    - $AT0_a = AT0_g + 1.14 (ALT_g – ALT_s)$

      $AT0_a$ is the altitude adjusted grid point value of AT0 (day °C)

      $AT0_g$ is the grid point value of AT0 from the dataset (day °C)

      1.14 lapse rate of AT0 (day °C/m)

      ALT_g is the altitude of the grid point from the dataset (m)

      ALT_s is the altitude of the site (m)
- Having obtained an altitude adjusted value the interpolated site value is calculated in four steps
    - Calculate the distance between the site and each reference grid point

      $$D_{sg} = \sqrt{(EAST_g - EAST_s)^2 + (NORTH_g - NORTH_s)^2}$$

      D_{sg} is the distance between the site and the grid point

      $EAST/NORTH_g$ is the national grid easting or northing for the grid point

      $EAST/NORTH_s$ is the national grid easting or northing for the site

      National grid references to 100 m in full numeric form
    - Calculate an inverse distance squared factor of each reference grid point

      $$W_g = \left[\frac{1}{D_{sg}}\right]^2$$

      W_g is the inverse distance squared factor for the grid point

      D_{sg} is the computed distance from the previous equation
    - Calculate a distance weighting factor for each reference grid point

      $$W_p = \frac{W_g}{W_t}$$

      W_p is the distance weighting factor for the grid point

      W_g is the inverse distance squared factor from the previous equation

      W_t is the sum of W_g values for all reference grid points (up to 4)
    - Obtain the site estimate for FCD, AAR or AT0 by calculating a distance weighted mean of reference grid points
      $V_s = V_{g1} W_{p1} + V_{g2} W_{p2} + V_{g3} W_{p3} + V_{g4} W_{p4}$

      V_s is the interpolated site value of FCD, AAR or AT0

      V_{g1}-V_{g4} are altitude adjusted grid point values of FCD, AAR or AT0 (FCD_a, $AT0_a$, AAR_a)

      W_{p1}-W_{p4} are distance weighting factors for grid points from previous equation.

- In summary, the current ALC climatic dataset (although dated) provides a single data source, which facilitates comparison between sites (i.e. all sites that are ALC Grade 1 have the same degree of limitation, e.g. for Grade 1, no or very minor limitations due to climate). The current climatic dataset is used to calculate ALC grades for wetness or droughtiness, based on historical climate data, rather than predicting wetness or dryness in soils for any period.

- Prior to the publication of the ALC climate dataset (Met Office, 1989) and the current ALC guidelines (MAFF, 1988), maps or meteorological station data were used to estimate site climatic parameters. Previous versions of the ALC included less specific guidance on grade cut-off values for climate and allowed more scope for professional judgement than the current version (MAFF, 1966; 1976). However, the manual interpretation of maps and the extrapolation of data (without specific guidance) relied on subjective judgements making comparison between sites more difficult than the current use of the single reference ALC dataset.

5 Suitability of current ALC climate dataset

- The current ALC climate dataset is based on data from 1941-1970 (rainfall and FCD) or 1961-1980 (temperature); which may make it unrepresentative of current climatic conditions. The ALC datasets have been reviewed on three occasions, in the 1990s and 2004 by ADAS and more recently by Keay *et al*. (2014). In this report we consider the suitability of the climate data currently used as part of the process of assessing soil wetness, i.e., field capacity and rainfall.

5.1 First review of ALC climatic datasets: ADAS, 1994

- Following the Met Office publication of rainfall and temperature data for the new international standard climatological period of 1961-1990, ADAS (1994) assessed the potential impact on ALC grading should the new dataset replace that in current use (the 1988 dataset[7]). The 1994 data reported that AAR had increased by 1-5% across England and Wales, in comparison to the 1988 ALC dataset (Figure 4). In most areas reported rainfall volumes were similar for the two datasets (<50mm differences) however larger changes were noted in high rainfall areas, particularly Cumbria and upland Wales.

- Figure 5, shows the climate grade for the 1994 dataset which shows that most of England and Wales is ALC Grade 1 for climate (i.e. there are few climate limitations to ALC). However, some areas of the north and west uplands have a lower grade for climate (e.g. ALC Grade 4 or 5). Differences in climate grades assessed using the 1988 and the 1994 datasets are shown in Figure 5b. Most grades are unchanged (83%), although in some areas of the north and west there is an increase of one grade or subgrade when using the 1994 dataset. The impact of the new climate grade is shown numerically in Table 3 for England and Table 4 for Wales. Overall, in England 11% of grid points were upgraded by 1 ALC grade, compared to Wales where 20% of grid points were upgraded by 1 ALC grade. It is important to note that the changes to climate grade will only change the overall ALC grade in situations where climate is the most limiting factor.

[7] The 1988 dataset is used to assess the ALC grade for climate (and as part of the assessment of other limitations). However, note that the Met Office did not publish this data "Climatological Data for Agricultural Land Classification" until January 1989 and as a result, it is often referred to as the 1989 dataset.

Table 3. England: change to overall climate grade from 1988 to 1994 climatic data at 5 km grid intersections (number of grid points). Blue: no change; green: upgrade (e.g. 2 to 1); orange: downgrade (e.g. 1 to 2). Source: ADAS, 1994.

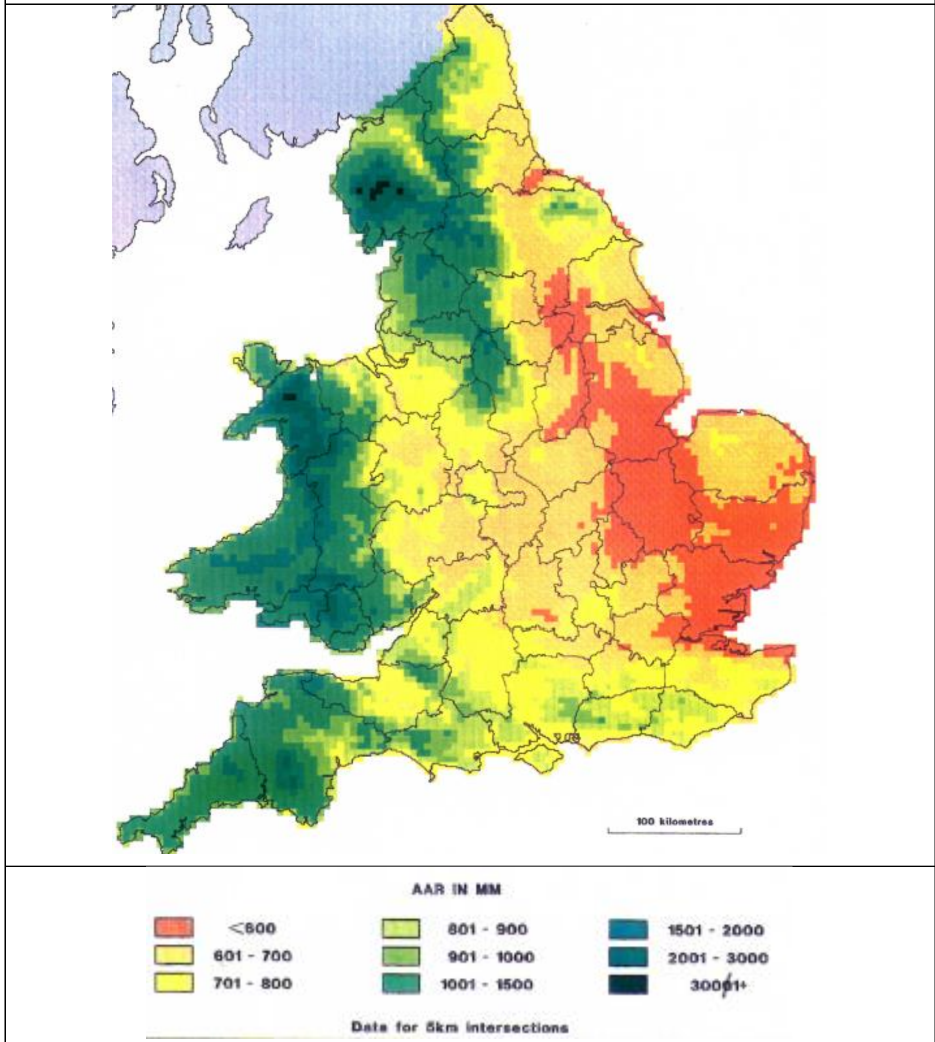
		ALC climatic data					
	Grade	**1**	**2**	**3a**	**3b**	**4**	**5**
1994 climatic data	**1**	3716	350	4			
	2	81	425	92	20		
	3a		42	83	53	4	
	3b		7	27	121	58	
	4			1	31	304	38
	5					15	64

Table 4. Wales: change to overall climate grade from 1989 to 1994 climatic data at 5 km grid intersections (number of grid points). Blue: no change; green: upgrade (e.g. 2 to 1); orange: downgrade (e.g. 1 to 2). Source: ADAS, 1994.

		ALC climatic data					
	Grade	**1**	**2**	**3a**	**3b**	**4**	**5**
1994 climatic data	**1**	191	60				
	2	9	87	27	7		
	3a		19	31	29	4	
	3b		5	11	79	43	
	4			2	20	247	25
	5					6	13

- The 1988 field capacity days (FCD) dataset was obtained directly from the SSLRC with values produced by regression using a series of regional equations in which the climatic variable was average annual rainfall. For comparison, ADAS (1994) computed the 1994 FCD dataset following the same principles used to derive the 1988 field capacity days using AAR values from the 1994 dataset. The regression used to calculate the 1994 field capacity days was a national equation obtained from SSLRC. FCDs were reduced in many areas reflecting the increased moisture deficits using the 1994 dataset, however ADAS (1994) noted that there were some anomalous increases in FCD in Cambridgeshire, Lincolnshire and South Yorkshire.
- ADAS (2004) used two methods to establish the impact of using the 1994 climate data on soil droughtiness and wetness assessments. For the first method a total of 78 soil associations were selected (covering between 65-70% of England and Wales) that provided a range of soils with widely differing profile characteristics such as soil texture, depth, organic matter content and permeability. A standard soil profile description was prepared for each soil series, specifying all the key soil characteristics required to assess wetness and droughtiness grade. A computer programme was used to combine the soil profile data with the climatic data to produce ALC grades according to wetness and droughtiness. A sub-selection of grades were manually checked for accuracy by experienced ADAS staff (10-20 for each soil type) giving a final sample of 1400 different soil/climate combinations (test locations). The results showed that wetness class was unchanged for 87% of the test locations, 13% were upgraded and 4% downgraded. In comparison, for soil droughtiness, one-third of the test locations were downgraded by either one grade or a sub-grade.

a. Average annual rainfall (AAR) 1961-1990 (mm)



b. AAR difference 1941-70 to 1961-1990 (mm)

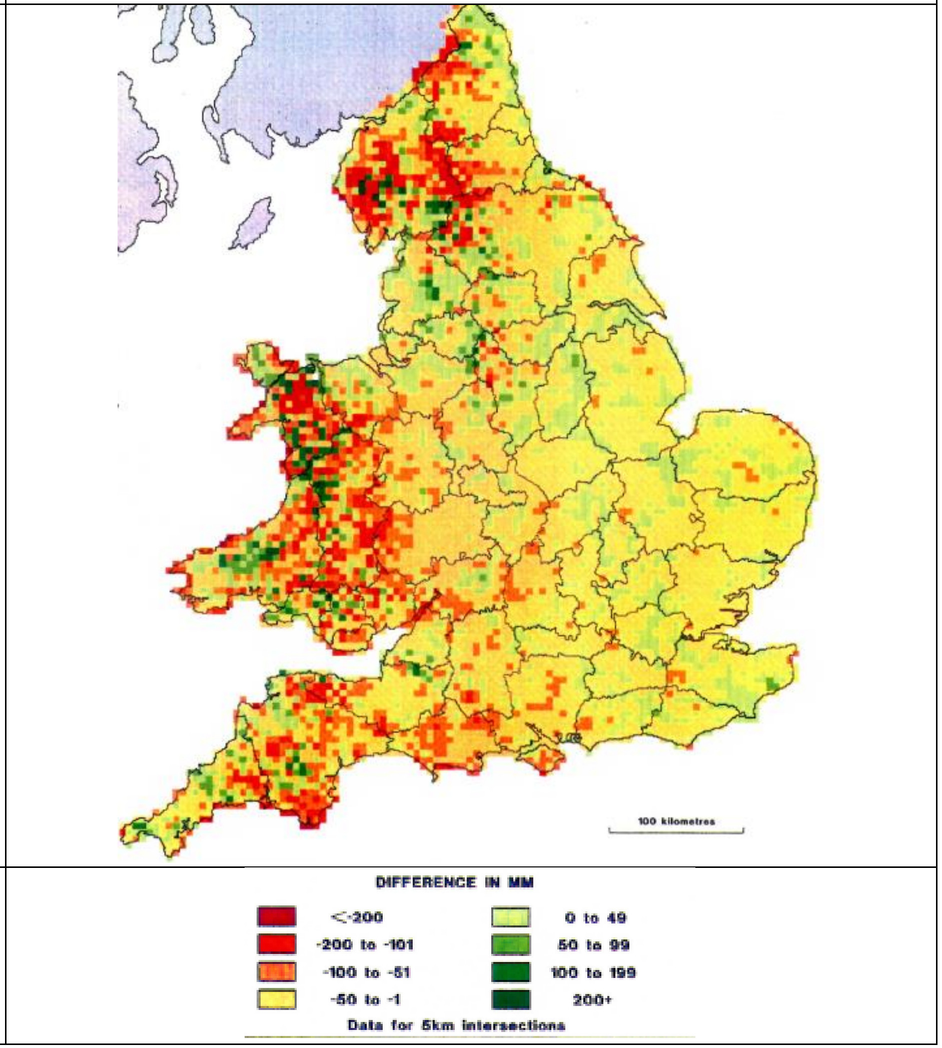


Figure 4. Average annual rainfall (AAR) in the a) 1994 dataset (AAR 1961-1990) compared to the b) 1988 ALC dataset (AAR 1941-1970). Source: ADAS 1994.

a. ALC climate grade using 1961-1990 data	b. Change in ALC climate grade between the 1988 and 1994 datasets

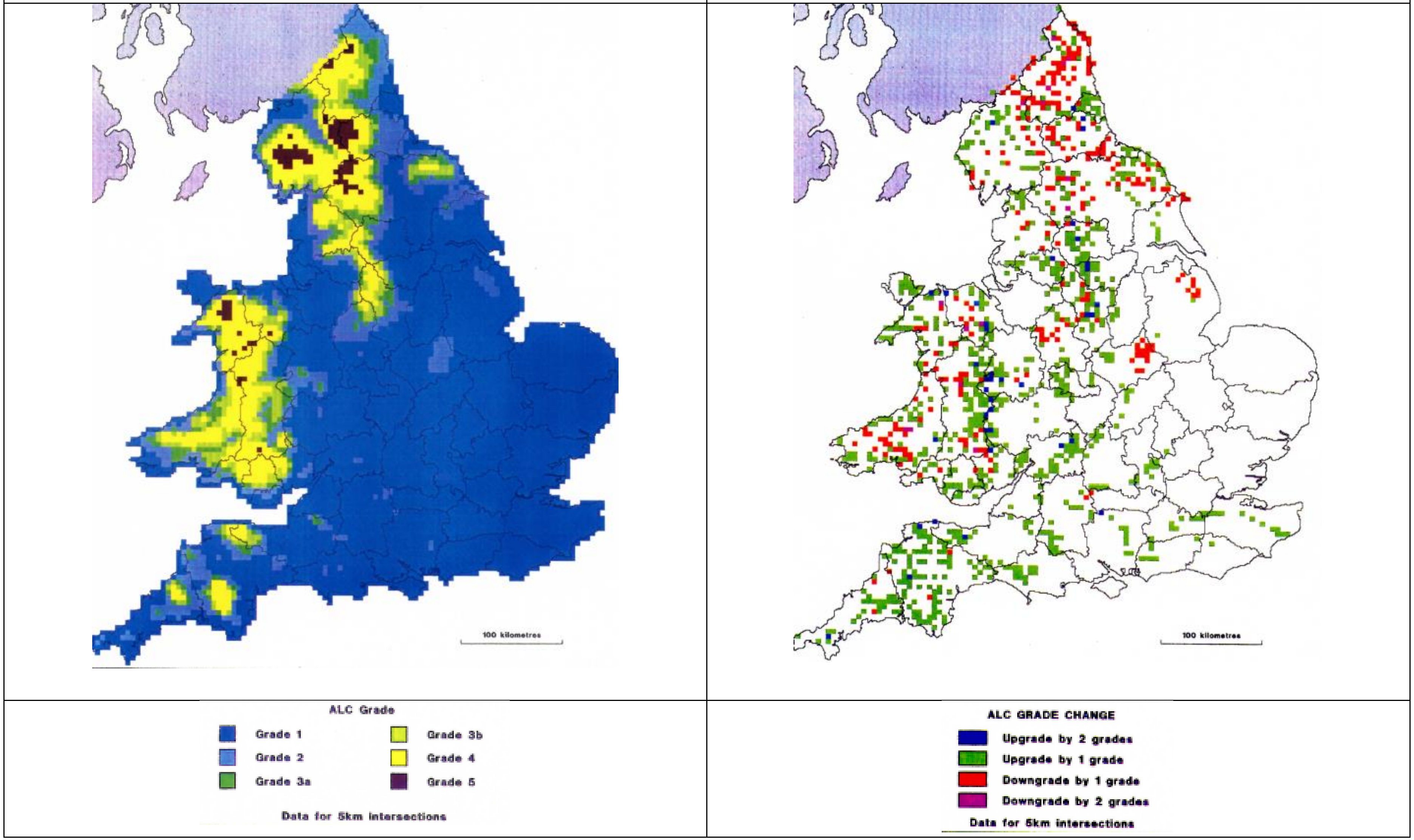


Figure 5. ALC climate grade using a) 1994 dataset compared to b) 1988 ALC dataset. Source: ADAS 1994.

5.1.1 Change in overall ALC grade

- Data from the National Soil Inventory (NSI) (data points at 5 km intervals across England and Wales) was used to compare differences in overall ALC grade using 1988 and 1994 climate data (ADAS, 1994b). ALC grades were calculated for each point by assessing the grade for climate, gradient, flooding, soil depth, stoniness, chemistry, wetness, droughtiness and erosion. The most limiting factors were then identified, and the resulting grade applied to the data point. Overall, there was little difference in the distribution of ALC grades using 1988 or 1994 climatic data (Table 5).
- The data showed that for England and Wales 17% (819) of the NSI datapoints changed ALC grade when the 1994 climate data was used. There was a noticeable downgrading from Grades 1 and 2 and subsequent increases (+25 NSI datapoints) in Grades 3a (mostly gains from Grade 2) and 3b (+194 datapoints) (elevations from both 3a and 4) (Table 6).

Table 5. Proportion of ALC grades (%) using 1988 or 1994 climatic data and the NSI dataset. Blue: no change; green: upgrade (e.g. 2 to 1); orange: downgrade (e.g. 1 to 2). Source: ADAS, 1994.

	Grade 1	Grade 2	Grade 3a	Grade 3b	Grade 4	Grade 5
1988 Data						
England and Wales	2.3	16.9	19.3	35.4	15.0	11.1
Wales	0.0	4.8	10.9	25.9	29.4	29.1
1994 Dataset						
England and Wales	2.0	14.0	19.9	39.4	14.7	10.1
Wales	0.0	3.9	10.3	28.2	29.8	27.9

Table 6. England and Wales: change to overall ALC grade using 1988 or 1994 climatic data and the NSI dataset (number of grid points). Blue: no change; green: upgrade (e.g. 2 to 1); orange: downgrade (e.g. 1 to 2). Source: ADAS, 1994.

		ALC climatic data					
	Grade	**1**	**2**	**3a**	**3b**	**4**	**5**
1994 climatic data	**1**	82	13				
	2	29	600	42	3	1	
	3a		200	693	64	2	1
	3b		3	199	1568	123	13
	4				77	591	41
	5			1		7	481

- Analysis of the most limiting factor showed that wetness, drought, climate and slope were the most important individual factors (Table 7). Overall, for England and Wales, wetness was the most limiting factor for 39% and 37% of datapoints using the 1989 and 1994 datasets, respectively. In comparison, droughtiness determined ALC grade at 17 and 21% of the datapoints using the 1988 and 1994 datasets, respectively. Only in the Southeast region was there a change in the relative importance of the limiting factors with wetness the most limiting using the 1988 dataset and drought the most limiting factor using the 1994 dataset.

Table 7. Most limiting factors (% of data points) for 1988 and 1994 climatic datasets and the NSI data. Yellow: most limiting factor. Grey: second most limiting factor. Source: ADAS, 1994.

Limit	England & Wales		Wales		Northern		Midlands & West		Eastern		Southeast		Southwest	
	88	**94**	**88**	**94**	**88**	**94**	**88**	**94**	**88**	**94**	**88**	**94**	**88**	**94**
Wetness	39.0	36.6	38.9	40.2	43.1	38.1	45.7	44.5	28.1	27.9	35.6	29.6	41.9	38.5
Drought	16.7	21.2	2.7	3.4	8.3	9.2	13.4	18.4	36.9	43.0	26.6	36.1	11.3	17.3
Climate	5.8	6.1	13.7	13.1	11.9	16.1	5.0	3.3	0.0	0.0	0.5	0.0	3.1	2.4
Slope	5.1	5.4	9.7	11.2	2.9	3.2	5.7	5.8	0.7	0.5	4.3	3.6	9.1	9.6

5.1.2 Spatial distribution of changes to soil wetness and droughtiness

- ADAS (1995) carried out an analysis using the 78 soil associations used in the ADAS (1994b) study to produce ALC grades according to wetness or droughtiness. Overall variation in grade for the different soil groups are shown in Table 8, below. Where the grade changes were potentially significant the changes in soil wetness and/or droughtiness were mapped for 56 soil associations. Example maps for the Hanslope (Pelosol) and Manod (Podzol) are shown in Figure 6 and 7, along with the accompanying Table 9 summarising the percentage change due to droughtiness and wetness.

Table 8. Percentage grade changes by soil group (Source: ADAS, 1995).

Soil group	Droughtiness			Wetness		
	Increase	**Decrease**	**Total**	**Increase**	**Decrease**	**Total**
Rendzinas	0	31	30	30	0	30
Pelosols	0	34	34	9	9	18
Brown soils	1	30	31	9	2	11
Podzols	3	31	34	6	3	9
Surface water gley	1	25	26	7	4	11
Ground water gley	1	24	25	7	12	19
Peats	1	0	0	6	4	10
All soil	3	28	29	10	4	14

- Around half of the soils had some significant change. Grade change was often concentrated at a local scale, which might be expected if there were consistent changes in the climate data. However, the changes were often interspersed with land that did not change grade leading ADAS to conclude that many of the changes were due to 'noise' in the dataset and likely to be due to climatic data processing methods and not real change. As a result, ADAS recommended that the ALC should continue to be based on the 1988 dataset.

Table 9. Changes in ALC grade for droughtiness and wetness for example Soil Associations Hanslope and Manod (Source: ADAS, 1995).

Soil Association	
Hanslope (Pelosol)	
Droughtiness	15% downgrading, generally greatest in the western and southern parts of the range
Wetness	Not significant
Principal	c.5% downgrade from 2 to 3a on droughtiness. None falls out of BMV
Comments	Could be significant downgrading of 2 to 3a in Essex.
Manod (Podzol)	
Droughtiness	31% downgrade across the extensive geographic range
Wetness	7% upgrade and 3% downgrade, mostly localised
Principal	This soil is 3b or 4 over most of the range in Wales but can be 3a in the South West. In this assessment there are many jumps of 2 grades in droughtiness and downgrading from 3a to 3b occurs on both wetness and droughtiness.
Comments	Highly variable pattern of grade changes demonstrates the noise factor in the datasets. Significant downgrading out of BMV in the South West

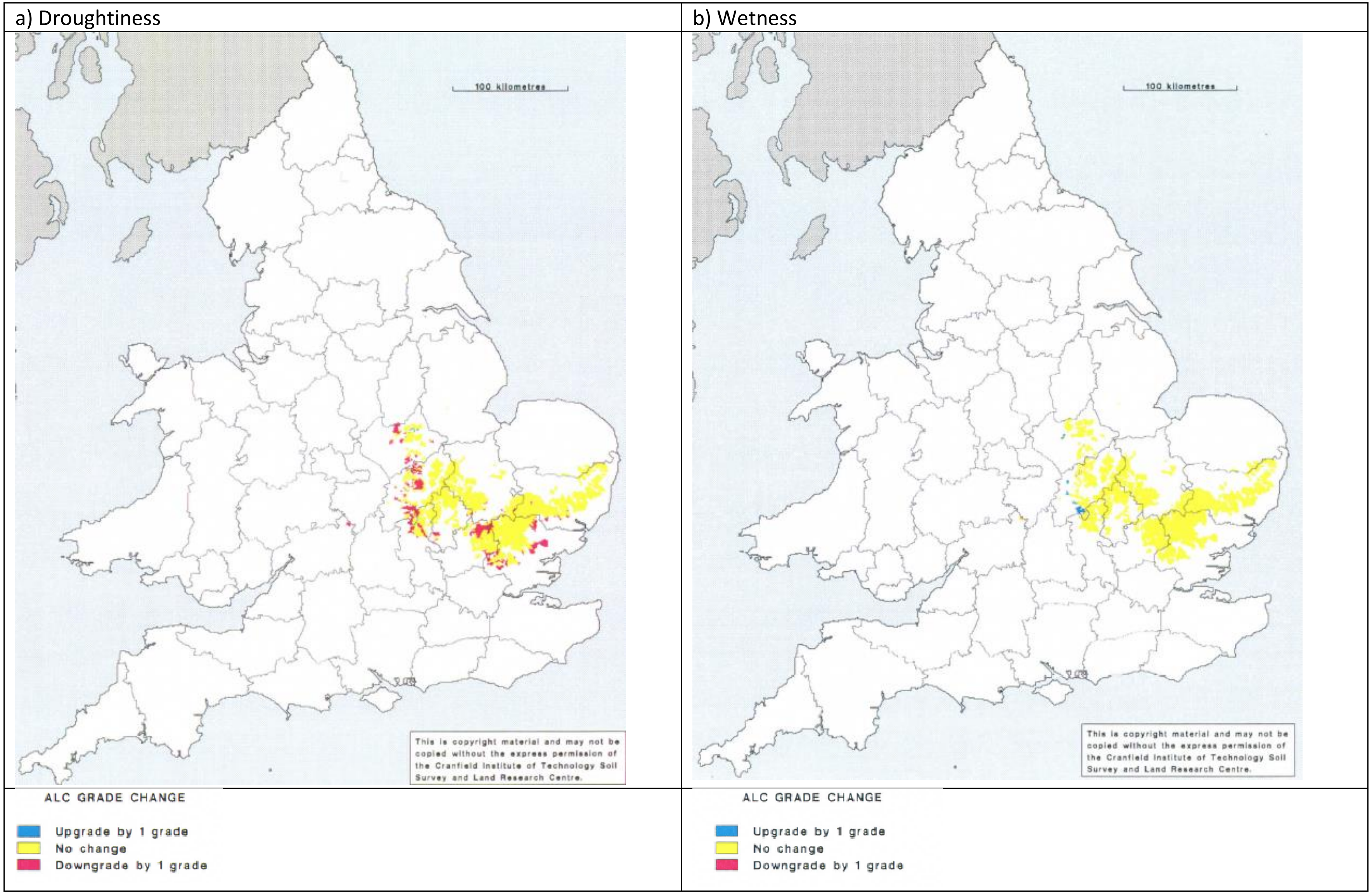


Figure 6. Hanslope Soil Series: change in ALC grade according to a) droughtiness and b) wetness (1988 compared to 1994 dataset). Source: ADAS, 1995.

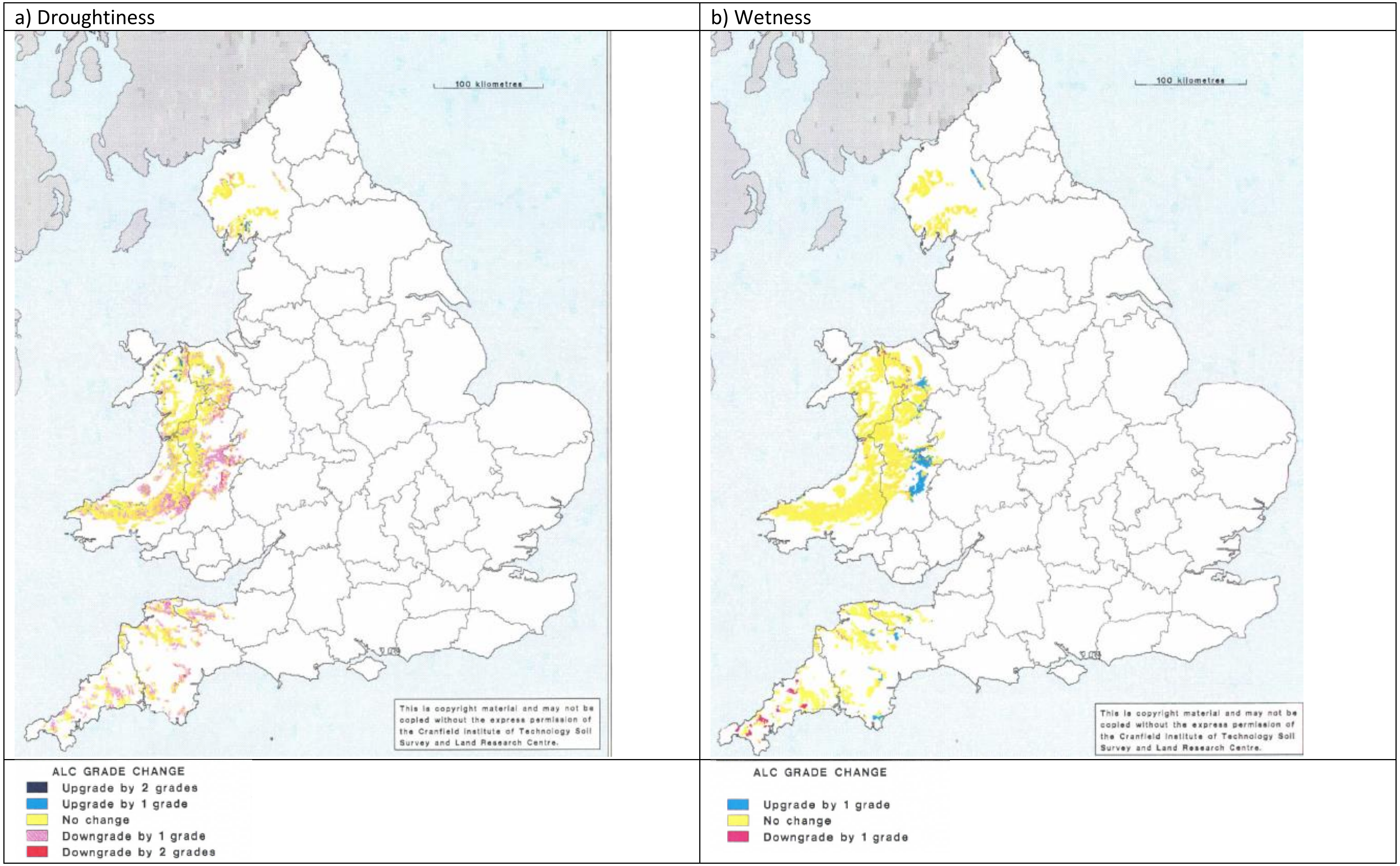


Figure 7. Manod Soil Series: change in ALC grade according to a) droughtiness and b) wetness (1988 compared to 1994 dataset). **Source: ADAS, 1995.**

5.2 ADAS (2004) review of ALC field capacity data

- In 2004, ADAS reviewed the climatological data currently used in the ALC following the recalculation of the climate averages in the UK by the Met Office for the period 1971-2000. In addition, to the station-based averages the Met Office also calculated monthly rainfall and temperature on a regular grid with 1 km intersections covering the UK (Perry and Hollis, 2005). The updated dataset adopted an 'interpolate then calculate' principle whereby all the interpolations were performed on the climate averages (i.e. climate-based averages from many stations were used to derive the gridded data, rather than building the regression from a subset of stations then interpolating across England and Wales). In contrast, the current ALC dataset (described above) uses a 'calculate then interpolate' principle in which, for example, AT0 was calculated for a sub-set of weather stations before being interpolated across England and Wales. The larger size of the dataset used in the updated methodology (interpolate then calculate) should provide a more representative estimate of current climatic conditions. In addition, the larger dataset will better capture the variability within the data (e.g., differences caused by altitude) than the data subset used to calculate the current (1988) ALC dataset. However, depending on the subject of interest a calculate then interpolate or interpolate then calculate approach may be most useful in a given situation (McVicar and Jupp, 2002). For example, some authors have noted that where sample sizes are small the calculate then interpolate procedures performed better than interpolate then calculate procedures (Bosma *et al*., 1994). Other authors have highlighted reduced computational cost of the calculate then interpolate approach compared to the interpolate then calculate approach (Leterme *et al*., 2007).

5.2.1 Changes in field capacity days

- ADAS (2004) used a subset of 22 agroclimatic areas and values for return to and end of field capacity (from Smith and Trafford, 1976). These were regressed against eastings, northings, altitude, average summer rainfall and average winter rainfall. Due to a measure of non-linearity the regressions were repeated separately for 'dry' areas where the AAR was <800 mm (FCD_{dry}) and 'wet' areas where the AAR was >800 mm (FCD_{wet}) (the authors note that this approximately equates to above/below 175 FCD). The equations are:
    - For areas with AAR<800 mm.

      FCD_{dry} = -78.62+0.2221*ASR+0.3085*AWR+0.2152*ALT+0.00082*E+0.00794*N
    - For areas with AAR>800 mm.

      FCD_{wet} = 47.50+0.0519*ASR+0.1856*AWR+0.1198*ALT+0.0054*E+0.00394*N

      Where FC is median field capacity duration (days), ASR is average summer rainfall (April to September, mm), AWR is average winter rainfall (October to March, mm), ALT is altitude in metres and E and N are eastings and northings.
- The predictive equation for the drier areas was tested against an additional sub-set of 11 agroclimatic areas (not used in the derivation of the equation) to check on the accuracy of the estimated data, Figure 8. The mean error over the 11 areas was 3 days, suggesting the regression was able to accurately estimate FCD.

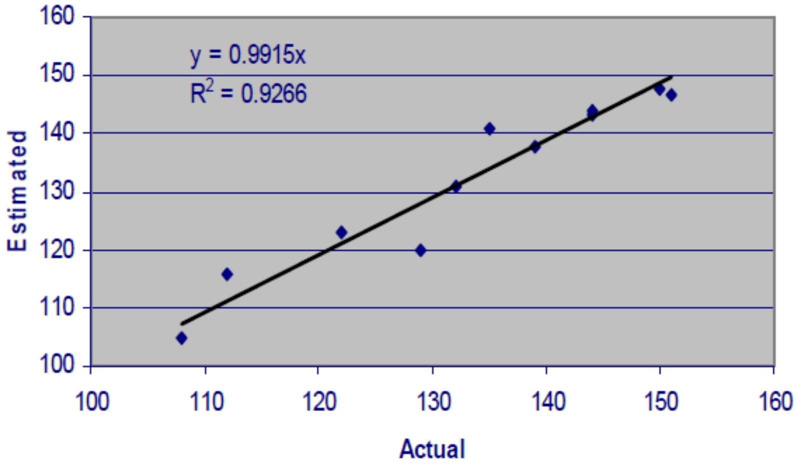


Figure 8. Check of FCD predictive equation. Actual: data from 11 agroclimatic areas from Smith and Trafford (1976) and estimated: calculated using ADAS equation for areas where AAR <800 mm (Source: ADAS, 2004).

5.2.2 Changes in rainfall

- Rainfall averages in the ALC climate dataset are based on the period 1941-1970. Variation in rainfall volumes and patterns would have effects on rainfall dependent ALC parameters. These include Field Capacity Days (FCD) as both average summer rainfall (ASR) and average winter rainfall (AWR) control FCD (ADAS, 2004). A comparison of the 1961-1990 and 1941-1970 AAR showed that there was little overall variation (±2%) (ADAS, 2004), although there was a notable increase in March rainfall (+16 to +36% depending on region) and decreases in July and August totals (-5 to -22% depending on region).

5.3 Comparison of methods for calculating field capacity

5.3.1 Field capacity methods

- Keay *et al*. (2014) used similar methodology to that used by ADAS (2004) (Table 10) but expanded the FC dataset to include 65 agroclimatic areas (from Smith and Trafford, 1976). In addition, data for ASR and AWR were normalised (using an inverse transformation, to eliminate the need for separate equations for wet and dry areas. The resulting equation (below) had an R^2 of 0.98 and small standard error of 6.4 days (this is referred to by Keay *et al*. (2014) as the '2010' method).

- FCD = 367.14-(55007.8*INVASR) + (25867.3*INVAWR) + 0.000564*E + 0.004383*N + 0.1*ALT

  FCD is field capacity days

  INVASR is inverse transformation of average summer rainfall (April to September, mm)

  INVAWR is inverse transformation of average winter rainfall (October to March, mm)

  ALT, altitude in metres

  E and N are eastings and northings.

- The authors note limitations to these methods include the lack of temperature data, the use of area-based averages rather than climate station values, the estimate of altitude from a range (in the original source data) and the difficulty associated with accurate identification of the end of field capacity.
- Keay *et al*. (2014) used Met Office Rainfall and Evaporation Calculation System (MORECS) estimates of FCDs to validate the estimate of FCDs derived used the new FCD equation (the 2010 method above) for 1961-1990. The MORECS system uses input from daily observations from 130 synoptic station to calculate evapotranspiration, soil moisture deficit and excess winter rainfall. The dataset was used to establish the end of FC (defined as the start date of a drying sequence of 10 days or more with a soil moisture deficit of ≥5mm) and the return to FC (defined as the start date of a wetting sequence of 10 days or more with a soil moisture deficit of < 5mm). From these two dates, the median or 50th percentile value for the start and end dates were calculated for the 30-year period and used to validate the‘2010’ method.
- Initial validation of the ‘2010’ method was carried out by comparison with data from 10 agroclimatic zones (15 datapoints) for areas with AAR <1000 mm. The mean bias (comparison of the two datasets, i.e. the agroclimatic data from Smith and Trafford, 1976 and the FCD values calculated by Keay *et al*., 2014 using the ‘2010’ method) was 17 days (i.e. the predicted values were 17 days higher than the actual values).
- The second stage of the validation compared the ADAS (2004) (the ‘2004’ method) and the ‘2010’ method (Keay *et al*., 2014) (Table 10) with the MORECS estimates (Figure 9). In drier areas the MORECS estimates (based on soil moisture deficits) had a lower number of FCD than the ‘2004’ and ’2010’ methods. However, where FCDs were >100, both predictive methods compared well with the MORECS data. A linear regression between the MORECS estimates and each of the predicted estimates of FCDs showed a strong relationship with an R^2 of approximately 0.93 for the ‘2010’ method (the R^2 for the relationship between the ADAS, ‘2004’ method and the MORECS estimated was not reported).

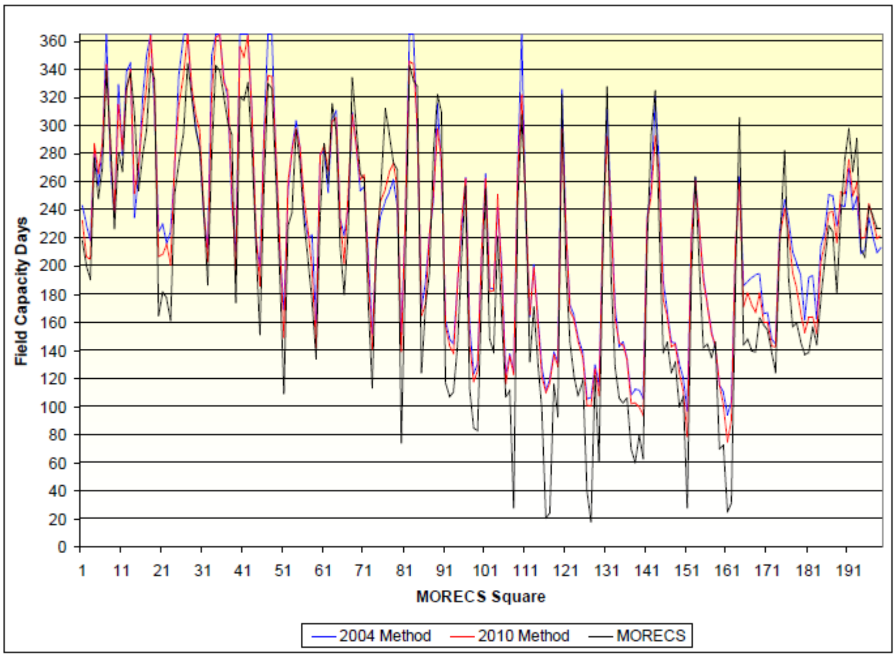


Figure 9. Comparison of 2004 (ADAS, 2004) and 2010 methods (Keay *et al*. 2014) for predicted field capacity days with MORECS data for the 1961-1990 period (Source: Keay *et al*., 2014).

Table 10. Equations for calculation of field capacity day (FCD) used by ADAS (2004) and Keay *et al*. (2014).

Method	Parameter	Equation	Summary
ADAS 2004	FCD dry	-78.62+0.2221*ASR+0.3085*AWR+0.2152 *ALT+0.00082*E+0.00794*N	FCD: median field capacity duration (days) ASR: average summer rainfall (April to September) (mm) AWR: average winter rainfall (October to March) (mm) ALT: altitude in metres E and N: Easting and Northings
	FCD wet	47.50+0.0519*ASR+0.1856*AWR+0.1198 *ALT+0.0054*E+0.00394*N	
Keay *et al*., 2014	FCD	367.14-(55007.8*INVASR) + (25867.3*INVAWR) + 0.000564*E + 0.004383*N + 0.1*ALT	FCD: median field capacity duration (days) INVASR: inverse transformation of average summer rainfall (April to September) (mm) INVAWR: inverse transformation of average winter rainfall (October to March) (mm) ALT: altitude in metres E and N: Easting and Northings

- For FCD between 100 and 225, the predictive methods compared well with the MORECS data, producing a positive mean bias (an overestimation) of 18-22 days and root mean square errors (a measure of how concentrated the data is around the line of best fit, lower values indicate a better fit) of 30-37 days (Table 11).

Table 11. Mean biases and root mean square errors (RMSE) of the '2004' (ADAS, 2004) and '2010' (Keay *et al*., 2014) methods for calculating FCD compared to measured data from MORECS for FCD between 100 and 225 (Source: Keay *et al*., 2014).

	Field capacity days	
	'2010' method	***'2004' method***
Mean bias	17.6	22.3
RMSE	30	37

5.4 Conclusions for climate data suitability

- Both ADAS (2004) and Keay *et al*. (2014) identified differences in temperature and summer rainfall, compared to the current ALC dataset. It is likely that the return to FC will be changed by lower ASR, which suggests that calculations based on the original ALC climate dataset may not be accurate. The ALC system should be reviewed using contemporary weather and crop yield statistics to determine the significance of the wetness factor for the grading of agricultural land in England and Wales.

- There is a need to update the ALC data on the duration of FC as it is currently based on 1941-1970 climate data. An important consideration is defining the start and end of field capacity. Based on the published methods of Francis (1981) and Smith and Trafford (1976), Keay *et al*. (2014) defined the end of field capacity as the start date of a drying sequence of 10 days or more with a soil moisture deficit (SMD)) of ≥5 mm. The authors defined the return to FC as the start date of a wetting sequence of 10 days or more with a soil moisture deficit of <5mm. Alternatively, the JRC (in the guidelines for applying common criteria to identify agricultural areas with natural constraints) defined field capacity as zero soil moisture deficit (Terres *et al*., 2016). The end of field capacity was defined as the period when soil moisture content was >0 mm for ≥5 consecutive days (during the first part of the year – before summer). And the start of the field capacity period was defined when ≥5 consecutive days had a SMD <0 mm (in the autumn). For comparison, the ALC guidelines (MAFF, 1988) state that FCD "estimate the duration of the period when the soil moisture deficit is zero"; the guidelines do not indicate the number of days at 0 SMD that is required to determine the start/end of field capacity.

- The published MORECS dataset would enable the identification of the start and end of field capacity based on, for example, the number of days when SMD = 0 mm. The MORECS dataset uses data from synoptic weather stations which is then interpolated to a 40 x 40 km gird (approximately 200 grid squares cover the UK). The dataset is available on a daily, weekly or monthly timescale. The relationship between SMD and other climate or location variables could be used to update the regression equation for predicting FCD. It is likely that the 'best' regression for predicting FCD will include both summer and winter rainfall, rather than simply annual rainfall which forms the basis of the current equation. Climate data suggests that annual rainfall has not changed significantly over time whereas changes to seasonal rainfall patterns have been noted which may affect both the start and end of FC.

6 Soil wetness and drainage

- Soil moisture condition is an important factor controlling agricultural production and nutrient losses to the environment through runoff or drainage losses (Jones *et al*., 2014). Soil drainage refers to the maintenance of the gaseous phase in soil pores by removal (or non-addition) of water (Rossiter, 2014). When a soil is poorly drained the space for the gaseous phase in the rooting zone is reduced. This has adverse effects on crop growth by reducing rooting. Excessive soil wetness also adversely affects seed germination and survival, partly because of anaerobic conditions and reductions in soil temperature. Soil wetness also influences the sensitivity of the soil to structural damage and is therefore a major factor determining the number of days when the soil is in a suitable condition for cultivation, trafficking by machinery or grazing by livestock. Consequently, temporal variations in soil moisture content and duration of 'wet' periods are important influences on land management practices.

- When a soil becomes saturated with water, downward percolation (internal drainage) will occur (provided the soil is sufficiently permeable). Percolation occurs when soil moisture content exceeds field capacity as the soil can no longer hold water against the pull of gravity; the rate of percolation depends on the amount of water in excess of field capacity (Jones *et al*., 2014), Figure 10. Travel time of percolating water through the soil matrix is regulated by the hydraulic conductivity, which varies from near zero when the soil is at field capacity to a maximum value when the soil is at saturation. However, note that in the presence of a high water table, no percolation may occur, resulting in longer periods when soil water content is above field capacity. When downward percolation stops, the soil is said to be at field capacity (Brady, 1984).

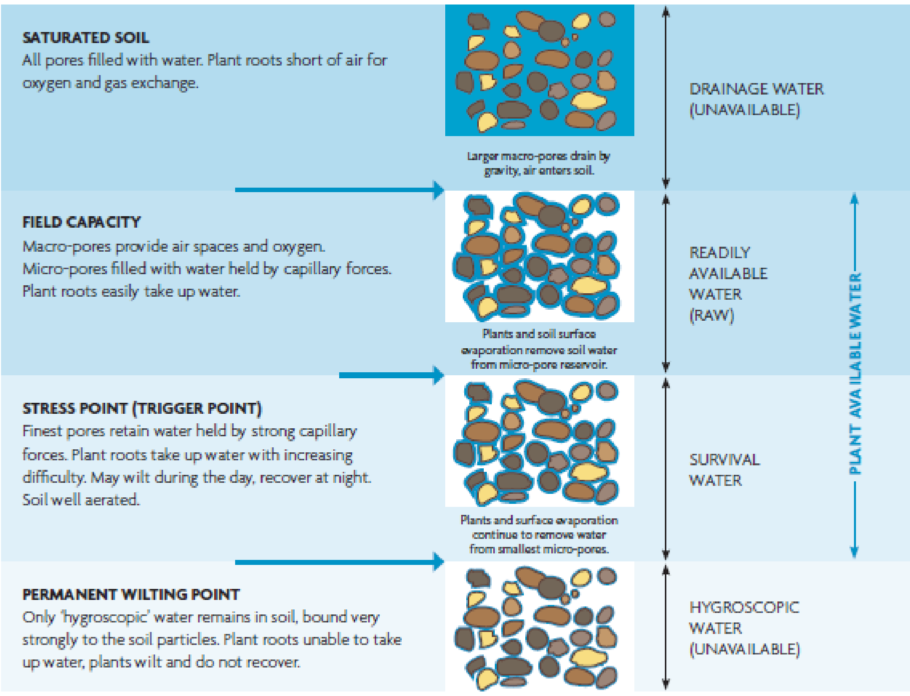


Figure 10. Soil water terminology (Source: Irrigation New Zealand)

- The soil classification for England and Wales (Avery, 1980) classifies two main types of soil affected by soil wetness. There are (a) two main groups of surface water gley soils and (b) seven main groups of groundwater gley soils (see Section 10.1 for more details). Surface water gley soils are created when water at the top of the soil moves slowly *down* the soil, due to reduced permeability somewhere in the profile. This can be due to combinations of soil texture and structure. This type of soil is common in England and Wales. Groundwater gley soils are the reverse. Here, water moves *up and down* the soil profile due to *groundwater* fluctuations, such as in river valleys. The ALC system is designed to cater for both situations.
- Duration of the period soil is saturated can be assessed using a water mass-balance model with a daily time step, by calculating soil moisture status from the cumulative balance of precipitation and soil water removal by evapotranspiration and percolation, and by taking account of antecedent soil moisture conditions (Jones *et al*., 2014).
- The maximum suction that can exerted to withdraw water from soil varies with crop type, but the generally accepted value is equivalent to about 15 times atmospheric pressure (i.e. 15 bar) (Shaxson and Barber, 2003). When soil water has been exhausted down to 15 bar tension, the water remaining in the soil will be stored in pores smaller than 0.0002 mm diameter and corresponds to the soil's permanent wilting point (Figure 10). Water held at tensions greater than the permanent wilting point is not available for plant growth. Hence, the total amount of soil water available to plants (known as TA_v in the ALC) is the volumetric (ratio of the volume of water to the unit volume of soil) soil water content between 0.05 and 15 bar tension (or for sands and loamy sands between 0.10 and 15 bar tension). These tensions approximate to field capacity defined as the point at which the soil moisture deficit is zero, (i.e. when all soil pores other than those that drain under gravity are full of water) and permanent wilting point (when the plants can extract no more moisture from the soil). It should be noted that other values may be chosen

to represent field capacity (e.g. 0.05, 0.06, 0.10 or 0.33 bar tension) depending on traditions and application needs in different parts of the world (Tóth *et al*., 2015).

7 Background to ALC wetness limitation

7.1 Soil wetness

- Several basic types of soil water regime have long been recognised: soils that are permeable and well drained, soils that are permeable but waterlogged by a fluctuating groundwater table, soils which are imperfectly drained and show evidence of gleying without a slowly permeable layer and soils that are slowly permeable and seasonally waterlogged. Although these basic groupings indicate waterlogging mechanisms and seasonal patterns of soil wetness for many purposes it is also important to know the relative duration of the waterlogging. Because of this Hollis, (1989), noted that some type of soil wetness classification was included in most national guidelines for soil description or land assessment. Typically, this included six or seven classes, based on the USDA drainage classes (e.g. USDA, 1951) identified from a set of broad guidelines (including soil gley morphology) and described as:
    - Rapidly or excessively drained
    - Somewhat rapidly (excessively) drained
    - Freely or well drained
    - Moderately well drained
    - Imperfectly drained
    - Poorly drained
    - Very poorly drained.
- ALC guidance prior (MAFF 1966 and 1976) to the current version (MAFF, 1988) used Soil Survey of England and Wales (SSEW) soil drainage classes to assess soil wetness. Note that SSEW drainage classes were as described above but omitting the 'somewhat rapidly (excessively) drained' class. However, whilst drainage classes give a good indication of the wetness of a soil and the speed of water removal the classes were subjective and did not indicate the duration of waterlogging. As a result, soil wetness classes were first introduced in the 1974 edition of the SSEW Field Handbook, which included six wetness classes based on depth/duration of soil wetness. This recognised that soil wetness state was more than just profile morphology (e.g. gleying) but related to periodicity of water in the rooting zone which is a combination of factors such as texture, structure and relationship with climate. Soil wetness classes were subsequently developed by Hodgson and Avery (1985) into the classes that appear in the current ALC guidelines (MAFF, 1988).
- The ALC method is based on the results of MAFF and SSLRC soil water regime monitoring projects carried out between 1964 and 1985 (Hollis, 1989). The MAFF/SSLRC soil wetness dataset details soil and site properties from 184 sites throughout England and Wales from two projects 1) MAFF/SSLRC soil water monitoring between 1974 and 1979 and 2) SSLRC dip well monitoring between 1964 and 1985. The joint MAFF/SSLRC project focused on surface water gley soils and a

limited number of widespread soil series[8]; after validation the dataset consisted of 233 site years of data from 123 sites (Hollis, 1989). However, because of the limited focus of the MAFF/SSLRC project the soils tended to have similar properties, i.e. all had a gleyed horizon within 40 cm and most also had a slowly permeable layer at the same depth. Therefore, to increase the range of soil types and properties (e.g. soils with a gleyed horizon between 40 and 70 cm or no gleyed horizon within 70 cm depth), selected data from the second study (SSLRC dip well monitoring) were added to the overall soil wetness dataset. This added 90 site years of data from 61 sites giving a total dataset of 323 site years from 184 sites (Hollis, 1989).

- Hollis (1989) reviewed the literature on relationships between the duration of soil wetness and gley morphology; this review forms the basis of the ALC assessment of soil wetness. In summary, he concluded that:

    1. Reddish soils from reddish geological formations can be wet for up to 120 days and show no gley morphology.
    2. Brownish horizons with no pale or grey mottles and only a few ochreous mottles are unlikely to be wet for more than a few days per year.
    3. Horizons with pale or grey colours on ped faces but not on the soil matrix and only a few ochreous mottles are not likely to be wet for more than 15 days a year.
    4. Horizons with common/many ochreous mottles but no pale or grey mottles may be wet for up to 35 days a year.
    5. Horizons with brownish or reddish colours dominant in the matrix and common/many grey or pale mottles are likely to be wet for 30-120 days a year.
    6. Horizons with pale or grey colours dominant on ped faces and pore faces and common ochreous mottles in the matrix are likely to be wet for 50-180 days a year.
    7. Horizons with pale or grey colours dominant in the matrix and common/many ochreous mottles are likely to be wet for 45 to >180 days a year.

- Overall, the review suggested that the more dominant the grey/pale colours and ochreous mottle were within a horizon the longer the duration of wetness. The main factors that affected the duration of wetness in a soil with a gley horizon were determined as, duration of field capacity period, soil hydraulic conductivity, presence/absence of slowly permeable layer and if field drainage was present. However, note that although horizons with gley morphology described in 4-7 above are likely to have been wet for at least 30 days on average Hollis (1989) noted that it was difficult to predict with any precision the duration of wetness from gley morphology alone.

7.2 Field capacity days

- The term field capacity is used in the meteorological sense to mean the condition of zero soil moisture deficit (Veihmeyer and Hendrickson, 1931 cited by Jones and Thomasson, 1985). Similarly , Jones *et al* (2014) defined field capacity as the maximum amount of water that a soil

[8] Soil profile characteristics are used to define soils at four levels in a hierarchical system, i.e., major group, group, subgroup, and series; the lower the category, the more precise is its definition. A soil series, the lowest category in the system, is a subdivision of a subgroup based on precisely defined particle-size subgroups, parent material (substrate) type, colour and mineralogical characteristics. Soil series are named after localities where examples are known to occur. Soil associations are geographic groupings of soils identified by the most frequently occurring soil series.

can retain solely under the force of gravity and is effectively the condition of zero soil moisture deficit.

- In the ALC, field capacity days (FCDs) estimates the duration of the period when the soil moisture deficit is zero. The ALC dataset for the median duration of field capacity is based on methodology developed by Smith and Trafford (1976) using rainfall and potential evapotranspiration data from 1941-1970. The method uses a standard water abstraction model for short-rooted crops and assumes that the crop transpires the first 50 mm of water at full potential rate, the second 50 mm at half potential rate and a further 25 mm at quarter potential rate. Median and quartile dates for the start/end of field capacity (listed in Smith and Trafford (1976) were later regressed with AAR by the SSLRC to generate a 10 km grid dataset, which has since been resolved to 5 km (Jones and Thomasson, 1985; Ragg *et al*., 1988). The datasets are held in LandIS and have also been published by the Met Office (1989); both can be used to obtain either grid point or interpolated values where sites are not located at a 5 km grid point.
- Smith and Trafford (1976), calculated field capacity data for 52 agroclimatic areas for England and Wales delineated according to geography and similarity of farming practices. Some of the areas were sub-divided into two areas when there was a notable change of farming type within the original area. The authors noted that as the choice of farming enterprise was driven by soil and climate the areas would have sufficient similarity that area-based averages of climate could be produced. Area-based averages were then adjusted for specific sites within a region. Within each agroclimatic area field capacity data was presented for a range of annual rainfall volumes, recognising that this was the most variable factor influencing drainage (Figure 12).
- To estimate the start and end of field capacity Smith and Trafford (1976) calculated monthly soil moisture balances for c.100 weather stations in England and Wales for each year of the 30-year period 1941-70, based on the method describe by Smith (1967). The soil moisture balance estimated the start (no moisture deficit) and end of the field capacity period (moisture deficit accumulating because of evapotranspiration). Once the start and end dates had been estimated the duration (days) of field capacity was calculated. Using this dataset, the authors calculated formulae linking the drainage climatic parameters with rainfall and transpiration for the major districts of England and Wales; the same formulae were used to calculate data for each agroclimatic area. A map of FCD was drawn by SURFACE II showing the isopleths at 25 day intervals; duration of FC is shortest in the Fens (<100 days) and longest in the uplands of Wales and northern England (Figure 11), Jones and Thomasson (1985).
- For each agroclimatic area, the median and lower/upper quartile dates were listed for 'return to field capacity' and 'end of field capacity'. Although an individual date is given for the median and lower/upper quartiles Smith and Trafford (1976) acknowledged that these have an error of ±3-4 days. In addition, the authors noted that adjustments should be made to the dates for late harvested cereals or sugar beet and suggested that return dates were likely to be 7-10 days later in early autumn and 15-20 days later in mid-winter following these crops. The difference is smallest if the autumn is wet and largest if the autumn/winter is dry because an extra 25 mm of rain was needed to replenish the soil following deeper rooted crops. Summer fallow would advance the return date as water is not taken up by crops.
- The end of field capacity is more difficult to estimate because it may be an intermittent process. Smith and Trafford (1976) noted that the results were the best estimate based on past weather. However, as April rainfall and the April transpiration are very nearly equal in most farm areas any small change in either parameter would have a major effect on the dating of the end of field

capacity. Consequently, the authors noted that the April figures could change by some 10-15 days following a very small modification of climatic conditions and dates for March or May were considered more reliable.

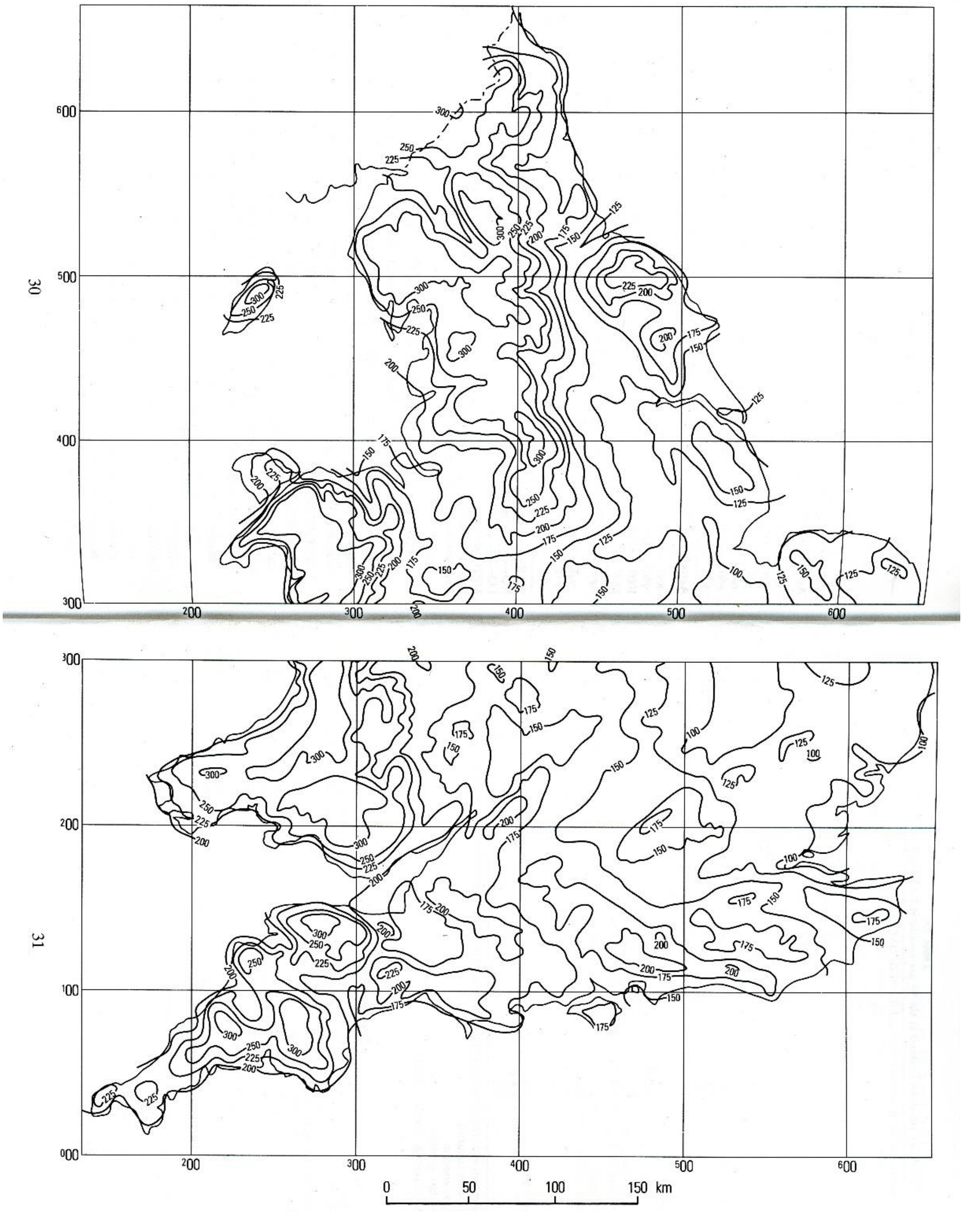


Figure 11. Median duration of field capacity (days) 1940-1970. Isopleths drawn by SURFACE II (Source: Jones and Thomasson, 1985).

- In 2014, the European Commission Joint Research Centre (JRC) reported on bio-physical criteria that could be used to define natural constraints for agriculture in Europe (Van Orshoven *et al.*, 2014). One of the criteria that was identified was ‘excess soil moisture’. Soil moisture was defined as “severely too wet when the number of days with soil moisture at or above field capacity is

≥230 days" (Jones *et al.*, 2014). The start of the period with soil moisture content at or above field capacity (surplus) is defined as the fifth day when 5 consecutive days fulfil the condition. Conversely, the end of the period occurs on the fifth day when at least 5 consecutive days have soil moisture content below field capacity (deficit). To account for between-year variability of soil moisture conditions a probabilistic approach was used to identify areas of excess soil moisture. An area was classified constrained if the probability of exceeding the severe annual limit was more than 20% of the number of years in the time series (for example in 7 years out of 30). Note that this probabilistic approach is different to that of the ALC which uses the median value for FCD over time. The example dataset for FCD in Table 12 shows the average and median FCD along with the probability of exceeding the ≥230 FCD threshold. For this example, only the probabilistic method results in the area being classified as severely limited. This is because the probabilistic method is better at capturing the range of the dataset than either the mean or the median. The ALC uses the median, which is a better measure of central tendency than the mean when the values being analysed have a skewed distribution.

Table 12. Example FCD dataset

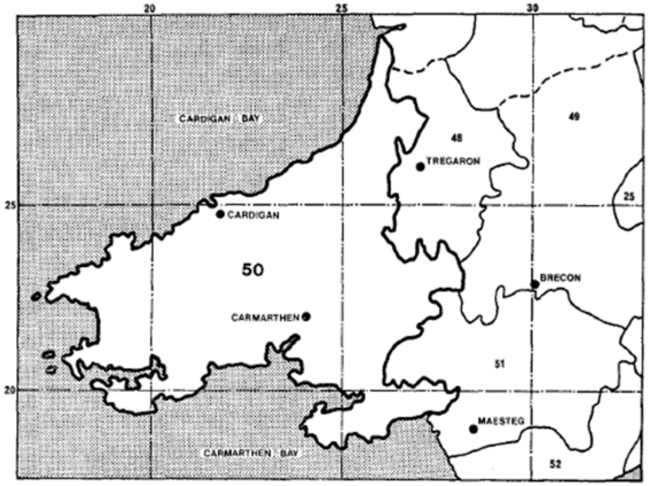
30-Year FCD dataset	Average	Median	Number of times ≥230 FCD
230, 200, 160, 200, **230**, 200, 220, 200, 190, **250**, **230**, 200, 160, 200, **230**, 200, 220, 200, 190, **250**, **230**, 200, 160, 200, **230**, 200,220, 200, 190, **250**	208	200	9 (30%)

- Table 13 details the relationship between field capacity days and suitability for agriculture reported in the literature.

Table 13. Field capacity days and suitability for agriculture

Field capacity days	Suitability for agriculture
≤175	Most large scale intensive arable farming in England and Wales
>175	Soils become progressively more susceptible to wetness and workability problems linked to climate.
>200	Large areas are in grassland and cereal cultivation becomes more marginal. Intensive agricultural systems begin to be adversely affected when average duration of field capacity is >200 days (Jones and Thomasson, 1993).
≥230	BMV land less common and constraints increase. Soil moisture is said to be severely too wet when the number of days with soil moisture at or above field capacity is >230 days (Jones *et al*., 2014).
>250	Around 250 FCD is considered the margin between intensive and extensive agriculture. The effect of wetness on agricultural operations will become very severe when duration of field capacity >250 days (Jones and Thomasson, 1993). Land work opportunities become progressively severely limited as FCD's rise beyond this point. This is due to prolonged wetness in the topsoil, even in inherently well drained soils. Most existing LFA in the UK is above 250 FCD.
>300	Areas >300 FCD are essentially mountains and moorland. Also, areas of blanket bog correlate closely with the 300 FCD isopleth. (Jones and Thomasson, 1985).

Area 50



HEIGHTS 0–123– 389 m
0–403–1280 ft

AREA AVERAGES

	J	F	M	A	My	Ju	Jy	A	S	O	N	D	
RAINFALL	131	89	82	78	84	76	85	110	119	125	139	140	mm
	5·15	3·5	3·25	3·05	3·3	3·0	3·35	4·35	4·7	4·9	5·45	5·5	in.
	Annual Total 1258 mm (49·5 in.)						**Range** 790–2000 mm (31–79 in.)						
POTENTIAL TRANSPIRATION	3	10	32	54	80	89	88	76	47	23	10	1	mm
	0·1	0·4	1·25	2·15	3·15	3·5	3·45	3·0	1·85	0·9	0·4	0·05	in.
	Winter Total 79 mm (3·1 in.)						**Summer Total** 434 mm (17·1 in.)						

Area 50 comprises the old Pembrokeshire and parts of Cardigan and Carmarthen (now Dyfed), including a high proportion of dairy farming and some general cropping to the south-west of the area.

Area 50

					Mean
Annual rainfall	mm in.	800 31·5	950 37·4	1100 43·3	**1258** **49·5**
Excess winter rain					
Lower Quartile	mm	215	320	430	**575**
Median	mm	290	410	525	**700**
Higher Quartile	mm	375	510	640	**825**
Return to field capacity					
Earlier Quartile		Sep 27	Sep 11	Aug 25	**Aug 5**
Median		Nov 3	Oct 17	Sep 28	**Sep 5**
Later Quartile		Nov 30	Nov 2	Oct 15	**Oct 3**
End of field capacity					
Earlier Quartile		Apr 5	Apr 12	Apr 18	**Apr 25**
Median		Apr 20	Apr 30	May 10	**May 20**
Later Quartile		May 10	May 25	Jun 10	**Jun 25**
Heaviest rainfall					
Expected in 1 day					
in 1 year	mm	22	25	29	**32**
in 2 years	mm	26	29	33	**36**
in 10 years	mm	35	39	43	**47**
Expected in 5 days					
in 1 year	mm	45	53	60	**67**
in 2 years	mm	53	61	69	**77**
in 10 years	mm	66	75	85	**95**
Soil moisture deficit					
End June					
Lower Quartile	mm	43	30	15	**5**
Median	mm	64	52	39	**27**
Higher Quartile	mm	90	83	74	**66**
End July					
Lower Quartile	mm	58	42	26	**10**
Median	mm	90	73	55	**36**
Higher Quartile	mm	104	93	82	**70**
End August					
Lower Quartile	mm	48	27	0	**0**
Median	mm	53	60	36	**19**
Higher Quartile	mm	115	95	75	**53**
End September					
Lower Quartile	mm	0	0	0	**0**
Median	mm	49	30	0	**0**
Higher Quartile	mm	101	77	50	**27**

Figure 12. Example data sheet for agroclimatic area showing the climatic parameters calculated by Smith and Trafford (1976) including return to and end of field capacity

8 Soil wetness limitation

- Soil wetness limitation is distinct from flooding, which is dealt with separately in the ALC system. A soil wetness limitation exists when the soil water regime adversely affects plant growth or imposes restrictions on cultivations or grazing by livestock (MAFF, 1988). The importance of this limitation is reflected by the widespread use of field drainage in both arable and grassland areas in England and Wales. According to Hill *et al*. (2018), around 6.4 million hectares of agricultural land in England and Wales have been drained with piped systems. The rate at which land was drained peaked during the 1960s to 1980s when grant aid was available. It is not known whether drains installed in that period continue to deliver effective drainage. ADAS (2002) note that it is "only those schemes installed within the last 40 or maybe 50 years which could be considered as having the potential to deliver effective drainage". However, ADAS (2002) also caveat that the potential for older drains to deliver effective drainage will depend on the standards of ditch maintenance since installation. In comparison, Hill et al. (2018) state that "given good maintenance, a useful life of at least 20 years can be expected and some systems can last many decades longer". Overall, it is suggested that field drainage may not be as effective as when initially installed, albeit that this cannot be confirmed.
- There are three main types of soil water regime, which give an indication of the overall mechanism and broad pattern of soil wetness:
    - Soils that are permeable and well drained
    - Soils that are permeable but waterlogged by a fluctuating groundwater table (i.e. Groundwater gleys
    - Soils that have restricted permeability and are seasonally waterlogged. – i.e. surface-water gleys
- The main factors that affect the duration of soil wetness are: (i) the presence of a fluctuating groundwater table, (ii) the presence of a slowly permeable layer (which inhibits the downward percolation of excess water causing seasonal wetness in and above the layer), (iii) the duration of the climatic field capacity period and (iv) whether there is artificial field drainage (Hollis, 1987). Of these factors the duration of climatic field capacity has a general controlling influence as it is a measure of the average period during which there is no potential soil moisture deficit so that any incident rainfall will produce excess soil water. At some time during this period, soils affected by a groundwater table or with a slowly permeable layer at shallow depth are liable to be wet. Thus, the longer the field capacity period the longer the likely duration of waterlogging in the soil. Any field assessment of soil wetness must consider all the factors above.
- The ALC wetness assessment considers three main factors
    - The climatic regime
    - The soil water regime
    - The texture of the top 25 cm of the soil

  To assess the ALC grade for soil wetness each of the factors are considered in turn before the final grade is allocated
- Assessment of the three factors identifies, 1) wetness of the cultivation zone or upper soil layers in grassland and 2) wetness in the full rooting zone/whole soil profile. The wetness of the

cultivation zone is influenced by the amount of water retained and the wetness of the climate. Soil texture is a major influence on the amount of water retained and for a given soil texture the wetter the climate the greater the poaching risk and potential workability challenges. However, although soil texture and climatic wetness are important characteristics affecting poaching and workability, waterlogging occurring below the cultivation zone is also important. Even if the subsoil waterlogging does not reach up into the cultivation zone the wetness of the zone may be increased by upward movement of water by capillary action (Jones *et al*., 1992). The effect of subsoil waterlogging depends on both the depth at which it occurs and the duration of that occurrence.

- To determine the wetness of the cultivation zone and the whole soil profile the ALC soil wetness assessment takes account of: i) the texture of the top 25 cm of the soil ii) the climatic regime and iii) the soil water regime (MAFF, 1988). To assess the ALC grade for soil wetness each of the factors are considered in turn before the final grade is allocated. Note that the ALC guidelines assume a good level of management, including the provision of field drains where necessary, therefore, the methodology for assessing soil wetness class considers drained soils only. It is not suitable for soils which are affected by high groundwater table which cannot be drained effectively; these soils need to be assessed using specialist knowledge and available data, on a case-by-case basis (MAFF, 1988).

8.1 Wetness of the cultivation zone

- As noted earlier the wetness of the cultivation zone is strongly influenced by:
    - The amount of water retained
    - The wetness of the climate

  These two factors are considered in the ALC wetness assessment through consideration of soil texture in the top 25 cm of the profile (to determine the amount of water retained) and median field capacity days (as a proxy for the wetness of the climate).

8.1.1 Soil texture

- Soil texture and structure have a major influence on water retention, water movement and aeration. These properties are key factors controlling workability, trafficability, poaching risk and the suitability of soil as a medium for plant growth (MAFF, 1988). Soil texture (of the top 25 cm) is used as part of the process for allocating the ALC grade according to soil wetness (1-5). For example, soils with a high clay content retain more water than those with a high sand content and are slower to return to a workable condition after wetting. Note that the top 25 cm of the soil is not synonymous with topsoil, which may extend down beyond 25 cm or be shallower than 25 cm. Where the texture varies within 25 cm the user must decide which texture is dominant in terms of effects on workability (Jones *et al*., 1992).

- Soil textural class is determined by the relative proportions of sand, silt and clay particles and the organic matter content. Particle size fractions used in the UK to determine soil texture are in Table 14.

Table 14. ALC particle size fractions (Source: MAFF, 1988).

Texture	Particle size fractions (mm)
Clay	<0.002
Silt	0.002-0.06
Sand*	0.06-2.0

*Sand may be further sub-divided into fine: 0.06-0.2 mm, medium: 0.2-0.6 mm and coarse: 0.6-2.0 mm size fractions.

- The mineral texture classes used for ALC are defined according to the soil textural triangle, which is based on the texture class intervals of the former Soil Survey of England and Wales. There are 11 major classes for mineral soil, which are defined by the relative proportions of clay, silt and sand within the soil (Figure 13). Note that for ALC purposes clay loam and silty clay loam are sub-divided according to clay content into medium (less than 27% clay) and heavy (27-35% clay); i.e., there are 13 classes.
- It should be noted that the particle size fractions classification groupings are not consistent throughout the world and the cut-off points between different particle size categories vary. For example, the US Soil Survey has the following cut off points, clay: <0.002, silt: 0.002-0.05, sand: 0.05-<2.0 mm, with groups further sub-divided into two (fine or coarse) clay/silt or five (very fine, fine, medium, coarse or very coarse) sand groups. Also, note that other systems use different textural classes, for example, the US system uses the category loam a broad class overlapping with several UK classes.
- In the ALC five texture groups have been defined according to water retention, workability characteristics and susceptibility to damage by grazing animals; for a given climate Group 1 is the most workable and Group 5 the least (Jones *et al*., 1992). The soil groupings are used in ALC as part of the procedure for allocating the final ALC grade according to soil wetness.
  - Peaty (PTY)
  - Sand (S), loamy sand (LS), sandy loam (SL) and sandy silt loam (SZL)
  - Silt loam (ZL), medium silty clay loam (MZCL), medium clay loam (MCL) and sandy clay loam (SCL)
  - Heavy silty clay loam (HZCL) and heavy clay loam (HCL)
  - Sandy clay (SC), silty clay (ZC) and clay (C).
- To allocate any soil to the correct textural group it must be accurately identified. Hand texturing may be appropriate for some samples but where a more accurate identification of soil texture is necessary laboratory analysis is likely to be required. This is most important where distinction between adjacent textural groups results in a change in ALC grade.

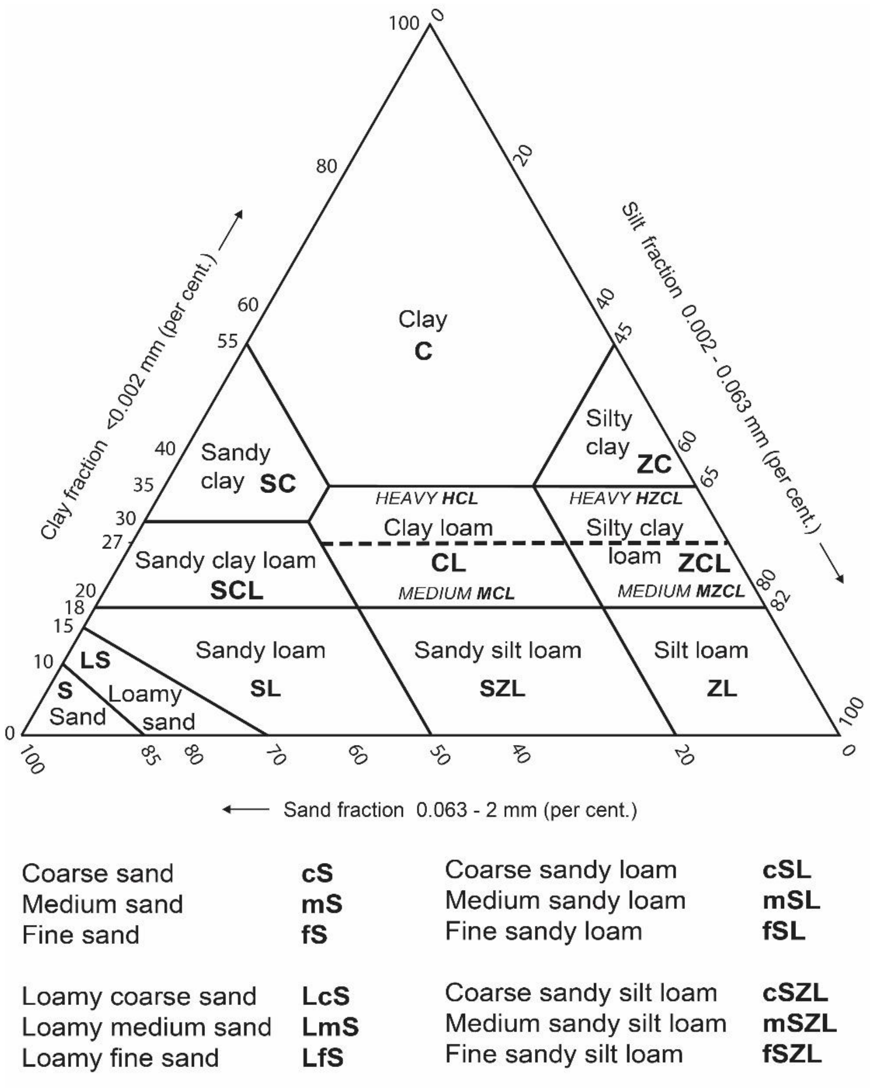


Figure 13. ALC soil textural triangle showing the heavy/medium clay loam and heavy/medium silty clay loam (heavy: 27-35% clay and medium: <27% clay). S, LS, SL and SZL may also be subdivided into coarse (>⅓ of sand has a particle size of >0.6 mm), medium (<⅔ fine sand and <⅓ coarse sand) and fine (>⅔ of sand has a particle size of <0.2 mm). (Source: Hodgson, 2022).

8.1.2 Climate and field capacity days

- The second factor affecting wetness in the cultivation zone or upper horizons is climate. For a given soil texture the wetter the climate the greater the poaching risk and workability problems. In the ALC, the parameter used as measure of climatic wetness is median duration of field capacity days (FCD). The criticality of this parameter has long been acknowledged and Smith (1976) noted that "the date of return of the soil to field capacity is of great importance to agriculture. It indicates the time about which the drains will begin to run and after which heavy rainfall is likely to cause flooding. After the return date, it is much more difficult to carry out cultivations and winter cereal sowing without doing damage to the soil and poaching of grasslands becomes more probable. The climatic suitability of a farm for arable or grassland husbandry is better expressed by this factor than any other single meteorological parameter" FCD are used in conjunction with soil texture and soil wetness class (I-VI) to allocate the final grade according to wetness. Note that the FCD parameter is also used as part of the procedure for assessing the duration of waterlogging in the whole soil profile.

- Soils usually return to field capacity during the autumn or early winter when rainfall tends to exceed evapotranspiration and the field capacity period typically ends in spring when evapotranspiration exceeds rainfall, and a moisture deficit begins to accumulate. The date of 'return to' and 'end of' field capacity will vary considerably across England and Wales. Soils will return to field capacity from late autumn or early winter in dry eastern areas and as early as August in the wetter west and north west (Jones *et al*., 1992). Where soils return to field capacity in early autumn opportunities for autumn cultivations or grazing without damage to the sward or soil will be limited; in some areas the return to field capacity is so early that the opportunities for cultivation in autumn are effectively nil and poaching risk will be high. When a site is at field capacity the soil moisture deficit is zero so that any rainfall must drain through the soil profile or via surface runoff. Where suction is less than 0.01 bar, soils will be wet. Thus, the longer the period of field capacity the longer the likely duration of waterlogging and cultivation/grazing opportunities are more severely limited.

- FCD is a meteorological rather than soil parameter and the values are derived from a mathematical model. FCD is used in preference to average annual rainfall (AAR) as it reflects the duration of wetness which is of relevance for field operations and incorporates evapotranspiration which also affects FCD. For example, lower average temperatures in the north of England, compared to the south will result in lower evapotranspiration. Therefore, two sites with the same rainfall (one in the south and one in the north) but different levels of evapotranspiration will have different FCD; the site in the north will have more FCD than the site in the south. As a result, FCD is a better indicator of the wetness of a site than AAR (Jones *et al*., 1992).

- FCD ranges are used as a proxy for climatic wetness zones; within each range similar soils are assumed to behave in a comparable manner in terms of workability or poaching risk. For a given soil texture the wetter the climate the greater the poaching risk and reduction in workdays. The choice of FCD ranges was based on field experience from ADAS advisory work and knowledge gained from previous ALC surveys (Jones *et al*., 1992). The ranges for mineral soils are <126, 126-150, 151-175, 176-225 and >225 and for organo-mineral/peat soils, are <126, 126-175, 176-225 and >225. The reasons for the different FCD intervals for mineral and organo-mineral/peat soils are not documented. However, in general there is no difference in the ALC grade allocated to mineral soils when FCD increase from 126-150 to 151-175 except for naturally calcareous soil. For naturally calcareous soil occurring in an area with not more than 150 FCD the ALC grade is increased due to the better structure and workability of these soils.

- ALC grade decreases as soil texture becomes finer and as FCD increases, albeit that moving to the next texture group or FCD does not always result in a grade/sub-grade change. Table 15, which provides the wetness grade for well-drained minerals soils shows the interaction between soil texture (in the top 25 cm) and climatic wetness (field capacity days). It illustrates that ALC grade generally decreases (in quality terms) with finer texture and therefore higher water retention, for example, where FCD are <126, the ALC grade for sandy loam (SL) is 1 compared to ALC Grade 3a for sandy clay (SC). However, as noted above moving to the next texture or FCD group does not always give a grade change. For example, where FCD are 126-150 site in both the first (S, LS, SL and SZL) and the second soil group (ZL, MZCL, MCL and SCL) are both ALC Grade 1 for soil wetness.

Likewise, for the second group (ZL, MZCL, MCL and SCL) sites in FCD groups <126, 126-150 and 151-175 are all allocated Grade 1 for soil wetness.

Table 15. Grade according to soil wetness for mineral soils (Source: MAFF, 1988).

Wetness class	Texture[1] Top 25 cm	Field capacity days <126	126-150	151-175	176-225	>225
I	S[2] LS[3] SL SZL	1	1	1	1	2
	ZL MZCL MCL SCL	1	1	1	2	3a
	HZCL HCL	2	2	2	3a	3b
	SC ZC C	3a (2)	3a (2)	3a	3b	3b

[1]. For naturally calcareous soils with more than 1% CaCO3 and between 18% and 50% clay in the top 25 cm, the grade where different from that of other soils is shown in brackets.
[2] Sand is not eligible for Grades 1, 2 or 3a. [3]. Loamy sand is not eligible for Grade 1.

9 Duration of waterlogging of the whole soil profile

- Although the soil texture of the top 25 cm and climatic wetness are important factors affecting workability and poaching risk these limitations are also affected by waterlogging occurring below the cultivation zone. Even if the subsoil waterlogging does not reach up into the cultivation zone the wetness of the zone may be increased by upward movement of water by capillary action. As a result, the water regime of the soil is important for workability as well as the effect which it has directly on crop growth.
- The severity of the effect of subsoil waterlogging depends on:
    - The depth at which it occurs
    - The duration of waterlogging.

Generally, the shallower and more prolonged the waterlogging the more severe the limitation. The criteria above are the basis of the six soil wetness classes (I-VI). Depth is defined by reference to three depth zones, i.e. <40 cm, 40-70 cm and >70 cm and duration is measured in days per annum.

9.1 Field assessment of soil wetness class

- As noted earlier (Section 7.1), ALC guidance prior (MAFF 1966 and 1976) to the current version (MAFF, 1988) used SSEW soil drainage classes to assess soil wetness. However, whilst drainage classes gave a good indication of the wetness of a soil and the speed of water removal the classes were subjective and did not indicate the duration of waterlogging. As a result, soil wetness classes were first introduced in the 1974 edition of the SSEW Field Handbook, which included six wetness classes based on depth/duration of soil wetness,
- Ideally, drainage status is determined by monitoring wells or measurements of the soil redox potential. However, this is often impractical and the ALC uses a methodology which was developed for field assessment of soil wetness from soil, site and climate properties. The procedure is based on the soil wetness dataset described in Section 7 and was developed, designed and calibrated by SSLRC (Hollis, 1989). Note that the soil wetness class is identified by roman numerals and is only part of the process by which the overall ALC grade (1-5) according to wetness is allocated. To determine the soil wetness in the field it is necessary to refer to a) the

duration of field capacity, b) the presence/absence of a gleyed horizon (a layer which is periodically wet indicated by the presence of grey or pale colours in combination with rusty mottles due to a lack of oxygen) and c) the depth to a slowly permeable layer (a layer which inhibits the downward percolation of excess water through the soil causing seasonal wetness in and above the layer). Once the soil wetness class (I-VI) has been identified it is combined with data on soil texture (top 25cm) and duration of field capacity to allocate the final ALC grade (1-5). Each of the factors are considered in the following sections.

- The first step in the process is to examine the soil profile to a depth of 1 metre to identify the presence of any peaty or organic mineral topsoil, the depth to gleying and depth to a slowly permeable layer. Secondly to establish whether the soil has been significantly disturbed or restored and thirdly to note whether the soil is reddish and has a slowly permeable layer starting within 80 cm but is not gleyed within 70 cm depth.
- Soil wetness is classified according to the depth and duration of waterlogging in the soil profile. Six soil wetness classes are defined, Table 16, although the current ALC Guidelines (MAFF, 1988) doesn't define 'wet'. Wet soil is defined in the SSEW Field Handbook as soil which "contains water removable at a suction of 1 kPa". In addition, "water films are visible on the surfaces of grains and peds. Excavation below a wet horizon will cause water to flow down the exposed face, though flow may be very slow and confined to major pores and fissures. Wet soil is normally below or a little above a water-table. The particle-size class of soil in the wet field state can be assessed without further moistening." As noted, soils can be allocated to a wetness class based on quantitative data or by the interpretation of soil profile characteristics, site and climate factors. The ALC user is guided by a decision tree (Figure 14) below which indicates the important parameters to consider at each point of the assessment process.

Table 16. Definition of soil wetness classes.

Wetness class	Duration of waterlogging
I	The soil profile is not wet within 70 cm depth for more than 30 days in most years[2].
II	The soil profile is wet within 70 cm depth for 31-90 days in most years or, if there is no slowly permeable layer within 80 cm depth, it is wet within 70 cm for more than 90 days, but not wet within 40 cm depth for more than 30 days in most years.
III	The soil profile is wet within 70 cm depth for 91-180 days in most years or, if there is no slowly permeable layer within 80 cm depth, it is wet within 70 cm for more than 180 days, but only wet within 40 cm depth for between 31 and 90 days in most years.
IV	The soil profile is wet within 70 cm depth for more than 180 days but not within 40 cm depth for more than 210 days in most years or, if there is no slowly permeable layer within 80 cm depth, it is wet within 40 cm depth for 91-210 days in most years.
V	The soil profile is wet within 40 cm depth for 211-335 days in most years.
VI	The soil profile is wet within 40 cm depth for more than 335 days in most years.

[1] The number of days specified is not necessarily a continuous period. [2] 'In most years' is defined as more than 10 out of 20 years.

- As noted earlier, waterlogging can occur because, i) the soil has a restricted permeability which inhibits the downward movement of excess water and at times causes saturation above the layer (surface water gley) and ii) where the soil is permeable, but waterlogging occurs because there is a permanently high or fluctuating ground water table (ground water gley). In both cases the duration of waterlogging is influenced by the wetness of the climate.

9.2 Method for undisturbed soils with a slowly permeable layer

- The key soil profile characteristics used to assess wetness class in soils with restricted permeability are depth to gleyed horizon and depth to slowly permeable layer. These soil characteristics are described in detail in following sections. There is an acknowledged relationship between depth to a gleyed horizon and wetness class; consequently, the ALC methodology requires a distinction to be made between soils which are not gleyed within 70 cm, gleyed within 70 cm but not 40 cm and gleyed within 40 cm. Similarly, there is a significant relationship between the depth to slowly permeable layer and soil wetness. Finally, the wetness class is also related to climate (field capacity days). Therefore, the three factors required to determine the wetness class of a soil which has a slowly permeable layer within 80 cm depth are:
    - Depth to gleyed horizon
    - Depth to slowly permeable layer
    - Field capacity days
- The decision tree indicates the Table or Figure in the ALC Guidance document that should be consulted to identify the wetness class of a range of soils. Coloured lines have been added to Figure 14, which are referred to below. It is only possible for soils with very specific criteria to be directly allocated into a soil wetness class directly from Figure 14. Most agricultural soils will be classified as undisturbed and so the user starts the decision tree by selecting ‘undisturbed’. Subsequently, the user will follow the appropriate pathway according to FCD, presence/absence of slowly permeable layer or gleying, depth to SPL or gleying and soil texture to guide the user to the relevant Table or Figure in the ALC guidance.

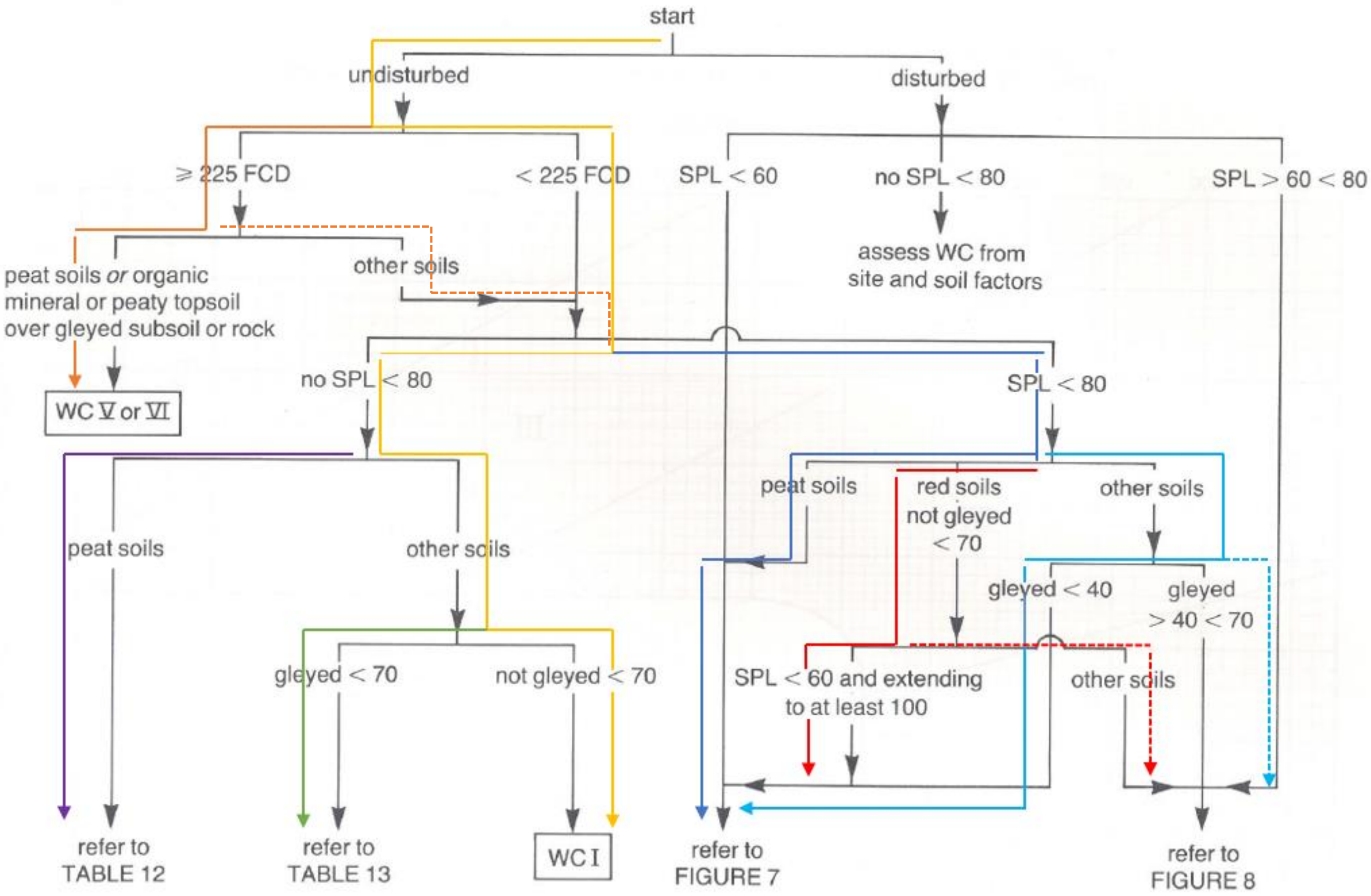


Figure 14. ALC Figure 6. Decision tree for assessing soil wetness class (WC) from field capacity days (FCD), depth to gleying (cm) and depth to slowly permeable layer (SPL in cm) (Adapted from MAFF, 1988).

- The wetness class of soils with a slowly permeable layer <80 cm and <225 FCD (yellow line, followed by blue, red or turquoise line in Figure 14) and mineral soils with a slowly permeable layer <80 cm and ≥225 FCD (yellow line followed by dashed orange line, followed by either blue, red or turquoise line in Figure 14) is established by reference to ALC Figures 7 and 8 (Figure 15 and 16, below). The basis of the figures is the regression analysis used to determine the number of FCD for critical waterlogging periods at 40 cm (W40) and 70 cm (W70) depth. For each site in the dipwell database (see Section 7) the number of FCD when W70 = 90 days (the boundary between wetness class II and III) when W70 = 180 days (the boundary between wetness class III and IV) and W40 = 210 days (the boundary between wetness class IV and V) was calculated.
- The figures define wetness class according to the combination of depth to gleying, SPL and FCD. Likewise, where the soil is undisturbed peat with <225 FCD and has an SPL <80 the user is also referred to ALC Figure 7 (yellow line, followed by the dark blue line), Figure 15 in this document. The wetness class is simply read from this figure; for example, where the depth to slowly permeable layer is 50 cm and the FCDs are 200 the soil wetness class is IV. Similarly, for an undisturbed mineral or organo-mineral soil with <225 FCD which has an SPL starting within 80 cm and gleying present within 40 cm depth the user is also referred to ALC Figure 7 (yellow, followed by blue, followed by turquoise line in Figure 14 in this document). However, if gleying is present within 70 cm depth but not within 40 cm (yellow, followed by blue, followed by turquoise, followed by dashed turquoise line in Figure 14 in this document), the user is referred to ALC Figure 8.

9.2.1 Red soils with a slowly permeable layer

- For soil that is undisturbed, has <225 FCD and is reddish (5YR or redder), not gleyed within 70 cm depth and with an SPL that starts within 60 cm depth and extends to at least 100 cm, the user is referred to ALC Figure 7 (yellow, followed by blue, followed by red lines in Figure 14), Figure 15 (below). For all other cases (where soils are reddish) the user is referred to ALC Figure 8 (yellow, followed by blue, followed by red, followed by red dashed lines). The wetness class is simply read from this figure; for example, where the depth to SPL is 50 cm and the FCDs are 200 the soil wetness class is III (Figure 16).

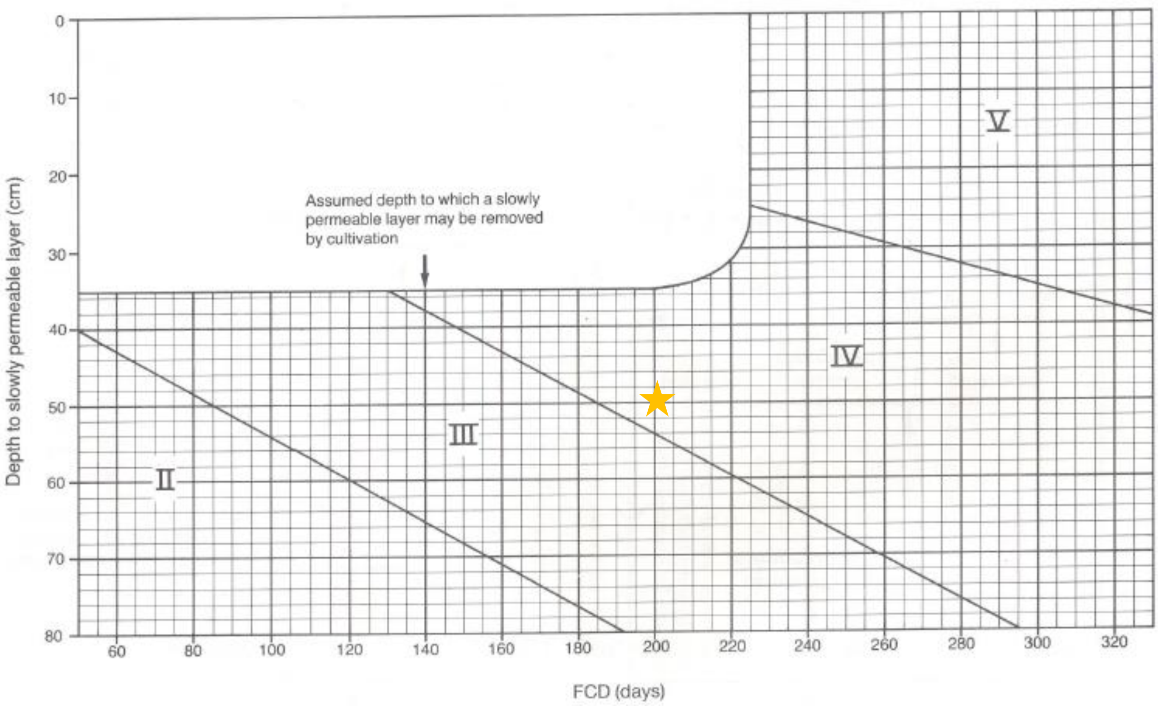


Figure 15. ALC Figure 7 for the estimation of wetness class from depth to slowly permeable layer and duration of field capacity (FCD) with gleying present within 40 cm depth and a slowly permeable layer starting within 80 cm depth. Also, for peat soils with a slowly permeable layer. Source: MAFF, 1988.

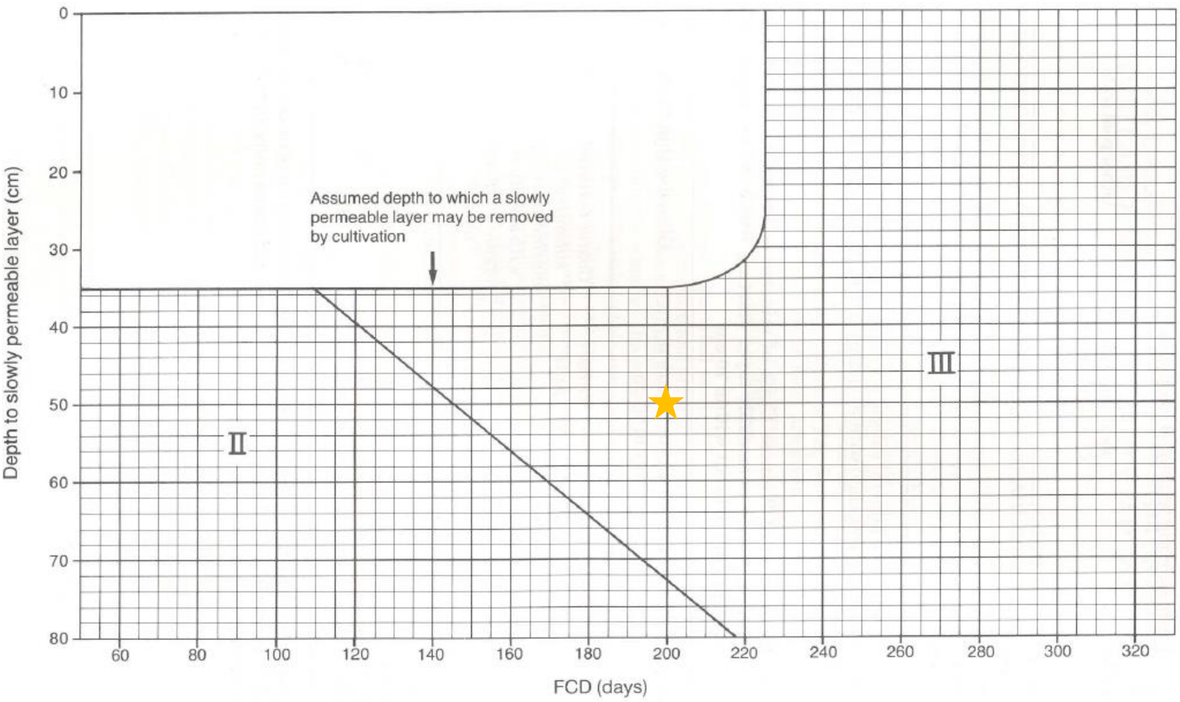


Figure 16. ALC Figure 8 for the estimation of wetness class from depth to slowly permeable layer and duration of field capacity (FCD) for soils with gleying present within 70 cm depth but not within 40 cm and a slowly permeable layer starting within 80 cm depth. Source: MAFF, 1988.

9.3 Method for undisturbed permeable soils with no SPL within 80 cm

- Waterlogging is generally of shorter duration if the subsoil is coarse textured and therefore very permeable. For this reason, the ALC methodology for assessing wetness class in soils which lack an SPL requires a distinction to be made between those with and those without coarse textured subsoils (Tables 17 and 18, below). This is because in these situations the hydraulic conductivity of the subsoil becomes an important criterion, and a rapidly permeable mineral subsoil typically has a higher hydraulic conductivity (and will drain faster) than a peaty subsoil.
- If the site has at least 225 FCD the topsoil is peaty or organic mineral texture with a gleyed subsoil or rock immediately below, the soil is Wetness Class V or VI (the orange line in Figure 14). Soils in Wetness Class VI are often perpetually waterlogged and will have standing surface water for long periods. Such soils are most likely to occur in areas with more than 300 FCD or in basin sites. Alternatively, where there is no SPL <80 cm the user is referred to ALC Table 12 (yellow line, followed by the purple line, Figure 14). ALC Table 12 indicates the soil wetness class for a range of FCD categories for peat soils with coarse textured subsoil and other peat soils (Table 17,below).
- Where the soil is undisturbed, has <225 FCD, no slowly permeable layer starting within 80 cm depth and no gleyed subsoil is present within 70 cm depth, the soil is Wetness Class I (the yellow line in Figure 14). However, where the same criteria apply but the soil is gleyed at <70 cm (yellow line followed by green line) the user is referred to ALC Table 13 (Table 18, below).

Table 17. ALC Table 12 estimation of wetness class of peat soils with no slowly permeable layer starting within 80 cm depth (Source: MAFF, 1988).

FCD range	Peat soils with coarse textured subsoil[1]	Other peat soils
≤100	I	I
101-150	I	II
151-200	I	II-IV
201-225	II	II-IV

[1]Peat soils in which the mineral subsoil horizons are predominately coarse textured (i.e. contain less than 18% clay) within 80 cm and are coarse textured at and immediately below 80 cm.

Table 18. ALC Table 13 estimation of wetness class or mineral or organo-mineral soils with no SPL within 80 cm but with gleying present within 70 cm (Source: MAFF, 1988).

FCD range	Gleyed within 70 cm but not within 40 cm		Gleyed within 40 cm	
	Coarse textured subsoil	*Other soil*	*Coarse texture soil or marine alluvium with a peaty or organo-mineral topsoil*	*Other soil*
≤100	I	I	I	I
101-200	I	I	I	II
201-250	I	II	II	III
>250	II	II	III	III

[1]Mineral soils in which the subsoil is predominately coarse textured (i.e. contain less than 18% clay) within 80 cm and is coarse textured at and immediately below 80 cm.

- Note that the relationship between FCDs for peat soils with no slowly permeable layer (Table 17) is based on limited data for drained peats (Hollis, 1989). Hollis (1989) recommends that more data from a wider range of drained peats is needed to substantiate the calculated critical FCD values given above.

9.4 Field assessment for disturbed soils

- Where the soil has been significantly disturbed or restored, the assessment of wetness class is made without reference to gleying as follows:
    - If there is an SPL within 60 cm the user is referred to ALC Figure 7 (Figure 15, this document).
    - If there is an SPL starting between 60 and 80 cm the user is referred to ALC Figure 8 (Figure 16, this document).
    - If there is no SPL within 80 cm, guidance suggests that the user should 'assess the likelihood and degree of waterlogging from any available evidence'.
- For disturbed soils the ALC guidance notes that severely compacted layers may be virtually impermeable (rather than slowly permeable) so that ALC Figures 7 and 8 (Figures 14 and 15 above) may underestimate the soil wetness class.

10 Soil characteristics used to assess soil wetness class

- Two soil characteristics are used in the field as part of the wetness class assessment: (i) the presence of a gleyed horizon and (ii) the depth to slowly permeable layer.

10.1 Presence of a gleyed horizon

- A soil horizon is a layer of mineral or organic soil material approximately parallel to the land surface that has characteristics altered by processes of soil formation. It differs from adjacent horizons in properties such as colour, structure and texture.
- The basic soil property used to identify horizons which are periodically wet is gley morphology, the presence of grey or pale colours in combination with rusty mottles or black ferrimanganiferous concentrations (Hollis, 1989). The process known as gleying is largely microbiological. (Burnham, 1980). Anaerobic microbes flourish in the absence of air under waterlogged conditions, reducing iron and manganese minerals. The chemical reduction of iron and manganese produces the characteristic gley colours. The oxidised ferric form causes the brown colouration of better drained soils (Jones *et al*., 1992). Some organic and red soils do not show these characteristics.
- There are two types of gley soil: 1) surface water gley, and 2) ground water gley. There are two main groups of surface gleys, (i) stagnogley (divided into four sub-groups) which occur widely in lowland Britain and (ii) stagnohumic gley soils, which have humose or peaty topsoil, which occur mainly in the uplands. There are seven types of ground water gley, alluvial, sandy, cambic, argillic, humic-alluvial, humic-sandy and humic with many sub-divisions (Avery, 1980). However, it is important to note that gleying can be observed in soil types other than gley soils.
- A key requirement for the ALC wetness assessment is to recognise whether a horizon is gleyed. Where gleying does not occur, the soil is likely to be freely drained. Red soils do not always exhibit signs of gleying and are assessed differently. The depth to gleying is defined as the distance in centimetres from the soil surface down to the top boundary of the uppermost gleyed soil horizon.

- Gleying provides some indication of the severity of the waterlogging in the soil. The closer the gleyed horizon to the surface of the soil the more likely the soil is to have poor natural drainage. However, note that gleying can also indicate poor drainage conditions in the past rather than currently (i.e. relict features). Consequently, wetness class cannot be determined by reference to gleying alone. Gleying cannot be used in disturbed soils and may be masked by strong parent material colour in red soils (Jones *et al*., 1992).
- In the ALC soil wetness the presence of a gleyed horizon is identified according to Table 19 below, which details the characteristics (and colours) that typify this horizon. There is no minimum horizon depth for a gleyed horizon in the ALC guidelines. This is accompanied by ALC Figure 4 (in Appendix 3 of the ALC) which illustrates the groups of colours on the Munsell chart which indicate gleying in the ALC (see Section 10.2). Jones *et al*. (1992) reported that this figure has been misinterpreted by some users and may need redesigning or redrawing in any future iterations of the ALC guidance. Also, note that more recent versions of the Munsell soil charts include specific pages relating to gleyed soils. Consequently, it is suggested that any updates to the ALC guidelines could potentially include reference to these charts specifically.
- The SSEW field handbook (Hodgson, 1976) describes mottle contrast as *faint*, *distinct* or *prominent*. However, ALC guidelines does not specify if the mottles in the context of ALC include all three categories of mottle. This should be clarified in any subsequent revisions to ALC.

Table 19. ALC characteristics of a gleyed horizon

	Identification
Gleyed horizon	Greyish or pale colours dominant in the matrix or on ped faces and at least 2% ochreous (rusty) mottles.
	Or, if it underlies an organic mineral or peaty topsoil and there are less than 2% ochreous mottles, grey colours are dominant in the matrix.
	Or, if reddish colours are dominant in the matrix, it has at least 2% greyish, brownish or ochreous mottles or ferri-manganiferous concentrations, and dominantly pale coloured ped faces
	There is no minimum thickness for a gleyed horizon in the ALC system.
Greyish	Munsell soil colour of any hue with chroma 2 or less and value more than 3 (see example in Figure 18).
Pale	Munsell soil colour of any hue with either chroma 3 and value more than 4 or chroma 4 and value more than 5;
Brownish	Munsell soil colour of hues 7.5YR to 10YR with either chroma 3 and value 4 or chroma 4 and value 4 or 5 (see example in Figure 19).
Ochreous	ochreous is Munsell soil colour of hue 10YR or redder with chroma more than 4 and value less than 7 (see example in Figure 19).
Reddish	reddish is Munsell soil colour of hue 5YR or redder.

- The critical depths to gleying are 40 cm and 70 cm because the process for assessing soil wetness class requires a distinction to be made between soils which are not gleyed to within 70 cm depth, those gleyed within 40 cm depth and those gleyed within 70 cm but not within 40 cm. If a gleyed horizon does not occur with 70 cm depth the soil is unlikely to be wetter than Class 1, unless it is reddish, disturbed or artificial. Likewise, if gleyed horizon does not occur within 40 cm depth the soil is unlikely to be wetter than Class III, even if a slowly permeable layer is present (Hollis, 1987).

- Some red soils do not exhibit gleying, despite having impeded drainage. It is therefore necessary to have a slightly modified procedure for assessing the wetness class of such soils. Red soils are defined as those having one or more horizons within 80 cm of the surface with a Munsell hue of 5YR or redder. The soil series mapped by the SSLRC which can have red, ungleyed slowly permeable layers are listed in Table 20, below.

Table 20. Reddish soils with a slowly permeable layer above 80 cm that generally do not display gleying (Source: Jones *et al.,* 1992).

Soil series	Soil association	Geology	General location
Clayworth Worcester	Worcester	Permo-Triassic reddish mudstone	Extensive in the Midlands and Southwest England, small areas in North England
Hodnet	Bromsgrove	Permo-Triassic Carboniferous sandstone and siltstone	Widespread in Midlands and Southwest England patches in Welsh Borderland
Hodnet North Newton	Hodnet	Permo-Triassic and Carboniferous reddish mudstone, siltstone and sandstone	Midlands and Southwest England
Tickenham	Whimple 1	Drift over Permo-Triassic reddish mudstone	Southwest England (Southwest Somerset & Avon)
Worcester	Whimple 3	Drift over Permo-Triassic and Carboniferous reddish mudstone	Widespread in Midlands and Southwest England
Dunnington Heath	Dunnington Heath	Drift over Permo-Triassic reddish mudstone	West facing slopes Soar Valley (North of Loughborough & South of the Trent)

- Hollis (1989) also described a slightly gleyed horizon. This has brownish or reddish colours dominant in the matrix and on ped faces and at least 2% ochreous, pale or greyish mottles. The depth to the top of the uppermost slightly gleyed layer could be used to determine the wetness class if the soil had no gleyed horizon. The slightly gleyed horizon was considered for inclusion in the 1996 revision of the ALC (1996) to "avoid the under-estimation of this limitation in some soils", principally in the Midlands, East and Southeast of England. However, the ALC was not subsequently revised and currently, the current ALC guidelines only consider the presence of a gleyed horizon not a slightly gleyed horizon. The concept of a slightly gleyed horizon could be a useful addition to the wetness assessment of any future iterations of the ALC guidelines.

10.2 Munsell soil colour

- Soil colour is assessed by comparing a freshly extracted moist soil sample with a standard Munsell soil colour chart which should be viewed in good natural light. The Munsell system is the internationally recognised method for assessing soil colour and allows for direct comparison of soil colour anywhere in the world.

- The Munsell colour system is a means to visually identify and match colour using a scientific approach. It is based on the three attributes of colour: hue, value and chroma (Figure 17). Hue identifies the basic spectral colour or wavelength, which is given a letter code, red (R), yellow (Y), blue (B), yellow-red (YR), green-yellow (GY) etc. There is normally one hue on each page in the Munsell Soil Colour Charts, although the gley colours are an exception. Within each letter range the hue becomes more yellow and less red as the numbers increase, e.g. 2.5 YR is redder than 5YR (the scale is 0, 2.5, 5, 7.5 and 10).
- Value is how light or dark a colour is on the Munsell system, and is indicated with a number, e.g. 2, 3, 4, 6, etc; the lower the value the darker the colour (0=black and 10=white). The value scale runs vertically with the lightest values at the top and the darkest at the bottom.
- Chroma is the colour intensity, saturation or relative strength of a colour, and in the Munsell system it is indicated with a number, typically from 0-8 (0 is no colour and 8 most colour, although some colours have higher maximum values). On the charts, the scale runs horizontally and goes from weak (on the left) to strong (on the right), for example, chroma 2 is weaker than 6. Gley charts are comprised completely of low chroma colours.

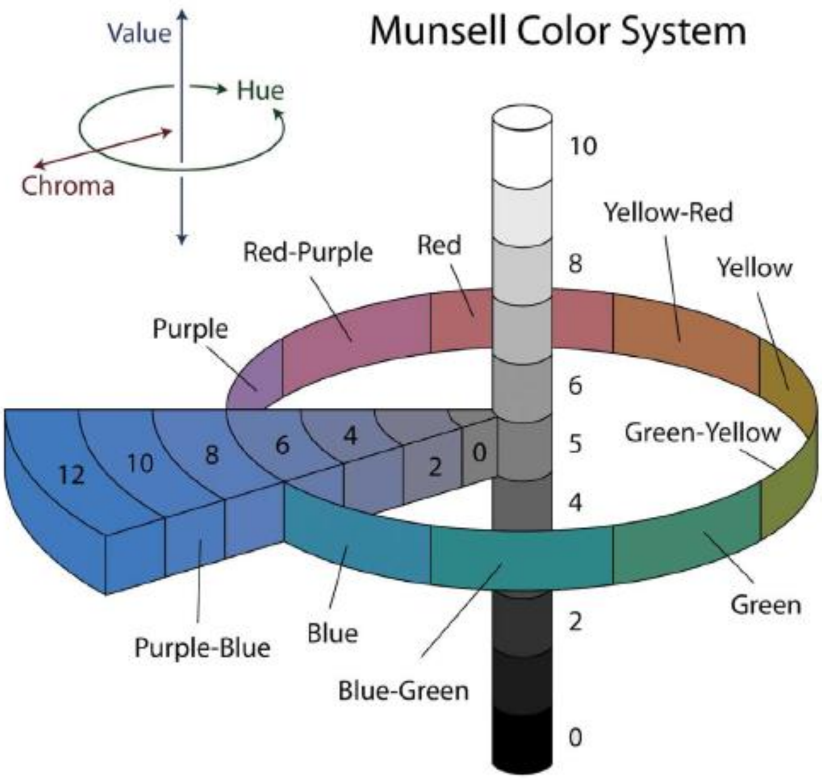


Figure 17. The relationship between hue, value and chroma in the Munsell colour system (Source: USDA, 2017).

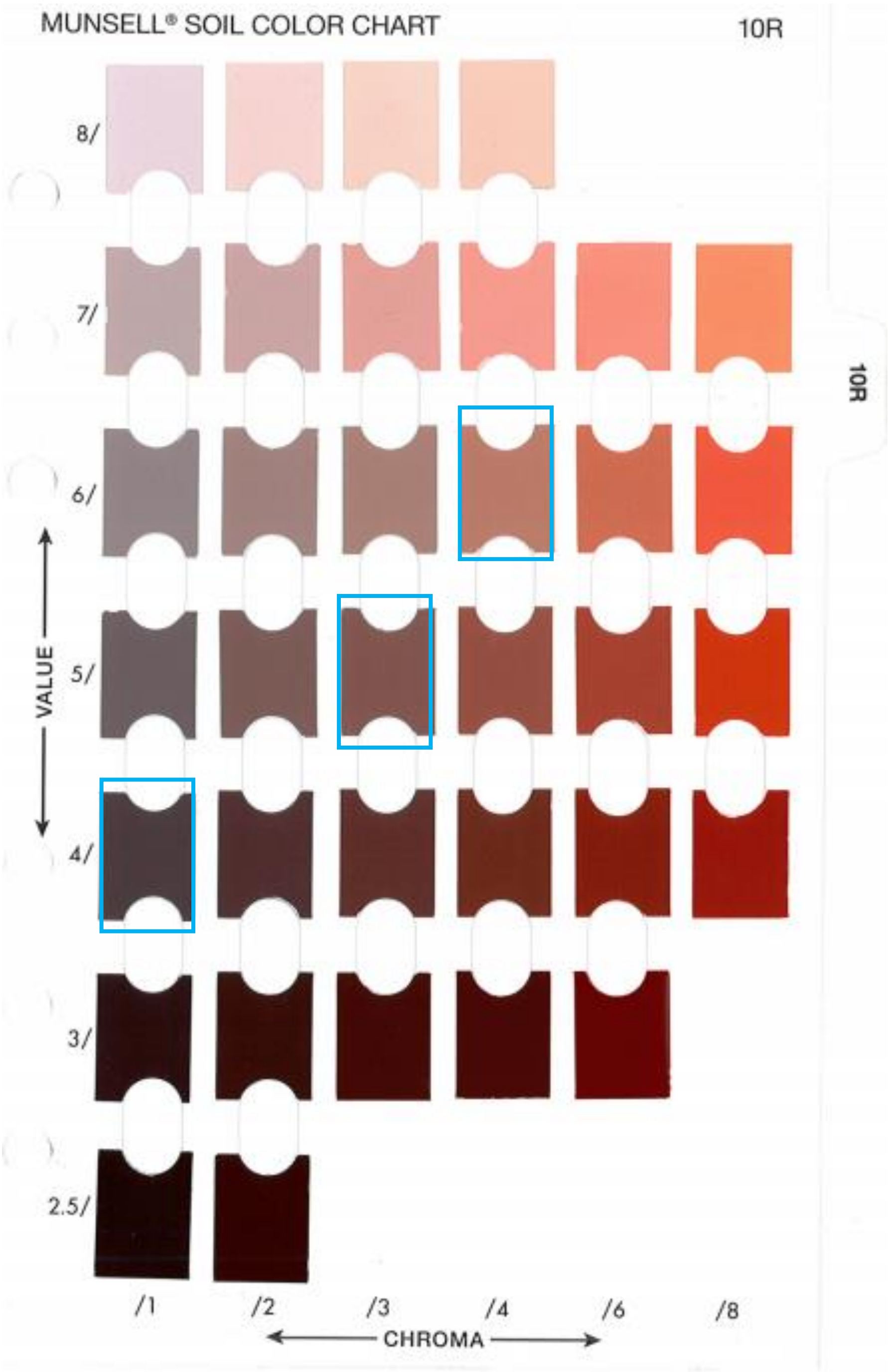


Figure 18. Example Munsell soil colour chart for hue 10 R. The highlighted cells are examples of ALC 'greyish' soil (any hue with chroma ≤2 and value >3), 'pale' soil (any hue with either chroma 3 and value >4 or chroma 4 and value >5).

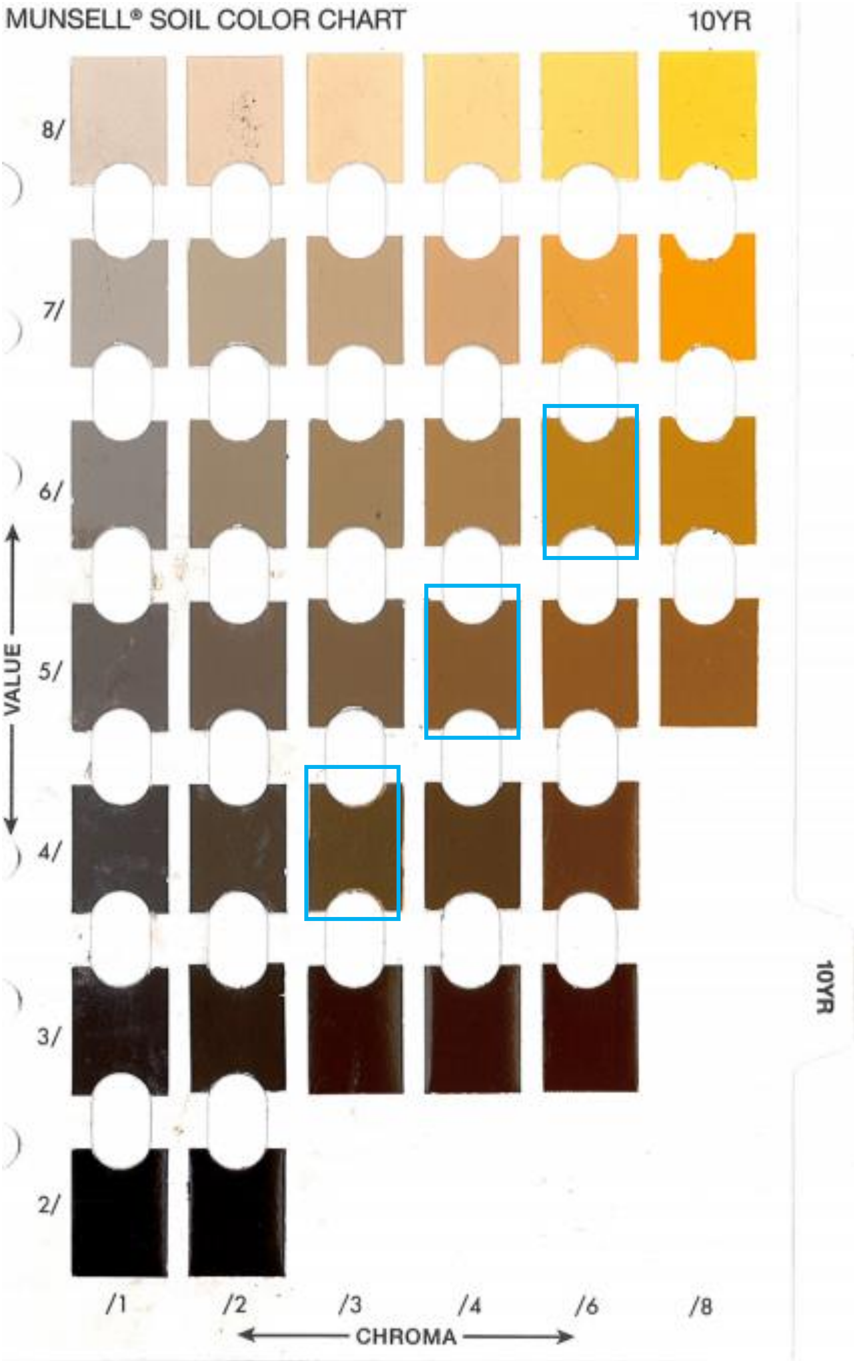


Figure 19. Example Munsell soil colour chart for hue 10 YR. The highlighted cell are examples of ALC 'brownish' soil (hue 7.5 to 10YR with either chroma 3 and value 4 or chroma 4 and value 4 or 5), ALC 'ochreous' soil (hue 10YR or redder with chroma >4 and value <7).

10.3 Depth to slowly permeable layer

- A slowly permeable layer (SPL) is one through which excess water can move only slowly, due to an adverse combination of soil texture, structure and porosity. As a result, drainage is impeded, and a SPL will have an important influence on the soil wetness. The SPL impedes downward percolation of excess water causing periodic saturation in the overlying layer. The impact of the layer is greatest when it occurs within 1 m of the soil surface. In addition, layers with a slow lateral hydraulic conductivity often have a slow vertical conductivity. Given slow vertical conductivity the lateral movement of water is particularly important as it controls the rate at which water flows into the field drainage system.
- Excess water removal from a soil horizon depends on its saturated hydraulic conductivity; the slower the saturated hydraulic conductivity of a horizon the more likely it is to be waterlogged for a significant part of the field capacity period (Hollis, 1989). Saturated flow occurs when the soil water pressure is positive, typically when about 90% of the total space is filled with water. Note, saturated hydraulic conductivity cannot be used to describe water movement under unsaturated conditions (USDA, 2017).
- Avery (1980) defined a slowly permeable subsurface horizon [layer] as one which "is at least 15 cm thick, starts within 80 cm depth, and acts as a significant barrier to water movement when the soil is saturated". Avery (1980) also stated that the slowly permeable horizon could be defined "in precise terms as having a horizontal saturated hydraulic conductivity of <10 cm per day. Many soil description systems distinguish one or more slow or low categories although the hydraulic conductivity value used to define the slow/low class is variable (Table 21). Units used to describe hydraulic conductivity vary in the literature; Table 22 shows the equivalent hydraulic conductivity in a variety of units.

Table 21. Saturated hydraulic conductivity classes from Thomasson, 1975; FAO[1]; USDA, 2017; Pettapiece, 1995 and Bell, 1985.

Classes of hydraulic conductivity	**cm/day**
Thomasson, 1975	
Very rapid	>1000
Moderate to rapid	100-1000
Moderate	30-100
Slow to moderate	10-30
Slow	1-10
Very slow	<1
FAO[1]	
Very rapid	>600
Rapid	305-300
Moderately rapid	151-305
Moderate	48-151
Moderately slow	12-48
Slow	3-12
Very slow	<3

Classes of hydraulic conductivity	cm/day
USDA Soil Survey Manual (USDA, 2017)	
Very high (≥100 µm/second)	>864
High (10 to <100 µm/second)	86.4 to <864
Moderately high (1 to <10 µm/second)	8.64 to <86.4
Moderately low (0.1 to <1 µm/second)	0.864 to <8.64
Low (0.01 to <0.1 µm/second)	0.0864 to <0.864
Very low (<0.01 µm/second)	<0.0864
Land Suitability Rating System for Agricultural Crops (Canada)	
Rapid	>360
Moderate	12-360
Slow	<12
Engineering Properties of Soil and Rocks (Bell, 1985).	
High (10^{-3} m/second)	>8640
Medium (10^{-3} to 10^{-5} m/second)	86.4 to 8640
Low (10^{-5} to 10^{-7} m/second)	0.864 to 86.40
Very low (10^{-7} to 10^{-9} m/second)	0.00864 to 0.864
Impermeable (10^{-9} m/second)	<0.00864

[1] https://www.fao.org/fishery/docs/CDrom/FAO_Training/FAO_Training/General/x6706e/x6706e09.htm#137a

Table 22. Saturated hydraulic conductivity in equivalent units (Source: USDA, 2017)

µm/s	m/s	cm/day	cm/hour	inch/h	kg s m^{-3}	m^3 s kg^{-3}
100	10^{-4}	864	36.0	14.17	1.02×10^{-2}	1.02×10^{-8}
10	10^{-5}	86.4	3.60	1.417	1.02×10^{-3}	1.02×10^{-9}
1	10^{-6}	8.64	0.360	0.1417	1.02×10^{-4}	1.02×10^{-10}
0.1	10^{-7}	0.864	0.0360	0.01417	1.02×10^{-5}	1.02×10^{-11}
0.01	10^{-8}	0.0864	0.00360	0.001417	1.02×10^{-6}	1.02×10^{-12}

- In the absence of measured conductivity, ALC guidance, in line with Avery (1980) defines a SPL as being at least 15 cm in thickness with the upper boundary within 80 cm of the surface and having the characteristics described in Table 23, below. For an undisturbed soil, the initial requirement is to establish if a SPL occurs within 80 cm of the soil surface. In comparison, for disturbed soil there are three categories for SPL, i.e. SPL <60 cm, no SPL <80 cm and SPL >60 and <80 cm.
- The ALC assumes that where FCD is <225 any SPL near the surface can be removed by cultivation; the assumed potential depth of loosening is 35 cm. For sites with FCD >225, there is no assumption that the SPL can be removed by cultivation, as the soil conditions are rarely suitable for effective loosening.

Table 23. ALC characteristics of slowly permeable layer (Source: MAFF, 1988).

1. Either	Clay, sandy clay, silty clay, medium clay loam, heavy clay loam, medium silty clay loam, heavy silty clay loam or sandy clay loam texture *and* massive, platy, medium or coarse or very coarse prismatic, weakly developed fine prismatic, coarse or very coarse angular blocky, weakly developed fine or medium angular blocky, or weakly developed coarse or very coarse subangular blocky structure.
Or	Silt loam, sandy silt loam, or any type of sandy loam with massive structure and at least firm consistence.
	In addition to the above, the following two criteria must apply:
A.	Less than 0.5% biopores (voids in the soil formed by biological activity, e.g. earthworms burrowing or plant roots; often tubular sharped) >0.5 mm diameter
B.	Evidence of wetness in, or immediately above the layer, such as ochreous mottles, ferrimanganiferous concentrations or gleying.

- The combination of texture, structure and consistence defined in Table 23 (either/or, above) are illustrated in Figure 20, below.

Structure / Ped size	Fine	Medium	Coarse	Very Coarse
Granular	Permeable			
Subangular blocky			Slowly permeable if >18% clay and weakly developed structure	
Angular blocky	Slowly permeable if >18% clay and weakly developed structure			
Prismatic			Slowly permeable if >18% clay	
Platy				
Massive	Slowly permeable if >18% clay or ZL, SZL, SL and at least firm consistence			

Figure 20. Combination of texture, structure and consistence for describing permeable and slowly permeable soils in ALC Figure 5 (note: biopore and evidence of wetness criteria must also apply) (Adapted from MAFF, 1988).

10.4 Summary: soil characteristics

10.4.1 Gleyed horizon and soil colours

- Soil colour is an important indicator of the drainage status. The main determinants of soil colours in most soils are mineral matter, organic matter, iron and manganese. Manganese can be an important indicator of wetness in red soils. Iron occurs in two oxidation states: reduced, as ferrous iron (Fe^{2+}), or oxidised, as ferric iron (Fe^{3+}). When iron is reduced, or in Fe^{2+} form, grey colour dominates the soil matrix. If adequate aeration has occurred, Fe^{2+} will lose electrons and exist as Fe^{3+} giving soil a reddish-brown colour and mottled appearance, typical of many agricultural soils. Areas in the soil where iron is reduced often develop characteristic bluish grey or greenish grey gley (colours with value of 4 or more on the gley pages in the Munsell colour book). Also, areas that have lost iron (reduced iron (ferrous iron) is soluble and enters the soil solution) typically develop characteristic grey or reddish grey colours (USDA, 2018). These changes in soil colour (and the depth at which they occur) are the basis of the identification of a gleyed horizon in the ALC. The nearer to the surface that gleying occurs, the wetter the soil is likely to be.

- Gley features develop in response to waterlogging which maybe recent or historic. The gley features may remain even though the waterlogged anaerobic conditions that created them no longer persist. For example, once formed, iron-oxide concentrations are stable in an oxidized soil and depletions remain pigment-free. Thus, some gley features may not reflect the current soil water regime because they formed under anaerobic conditions that no longer exist. This should be noted in any subsequent revisions to the ALC.
- An important component of the identification of a gleyed horizon is the allocation of the Munsell colour of the soil matrix and/or mottles. However, the ALC currently gives no guidance on how to determine the Munsell soil colour. Consequently it is recommended that the ALC includes additional guidance on how to use a Munsell colour chart (e.g., comparing a freshly extracted moist soil sample with standard Munsell soil colour charts in good natural light, colours can appear redder when the sun is low in the sky,). It is also recommended that ALC Figure 4 is redrawn or replaced to improve clarity. In addition a footnote to ALC Figure 4 could include some guidance on how to use a Munsell soil colour chart.
- The Munsell method for assessing soils is at best semi quantitative, because it is limited by a subjective match and by the number of Munsell colour chips (Baumgardner *et al*. 1985). For example, Shields *et al*. (1966) found that 12 experienced observers agreed on the Munsell value of samples within a range of between 0.5 and 2 units, the average variation was 1 unit. Also, Post *et al*. (1993) found that soil scientists agreed only 52% of the time on the same colour chip for all three colour components. However, note that in ALC, colour is used primarily to (a) assess if a soil is brown or red and (b) to allocate a hue/value/chroma combination into a brown, pale, grey or ochreous category (ALC Figure 4). Consequently, attribution to red, brown, pale, grey or ochreous is critical but the specific colour combination of hue, value and chroma within red, brown, pale, grey or ochreous groupings is much less important.
- Other potential methods for determining soil colour have been investigated including colorimeters and smart phone cameras. Moritsuka *et al.* (2019) compared soil colour determined using Munsell soil colour charts with results from low-cost colorimeters (CS-10, Cube, Nix Pro, and Color Muse at <$500) and conventional colorimeters ((SPAD-503, CR-20, CR-400, and CR-410 at >$3000). In their experiment, air-dried soil samples, which had been prepared using 2-mm sieving were measured visually using a Munsell colour chart and with colorimeters. The authors noted that overall, instrumental measurement was much more repeatable than visual observation. However, both the repeatability and stability of the low-cost colorimeters tended to be lower than those of the conventional colorimeters, albeit sensitivity of the low-cost colorimeters was still much higher than that of the visual method., Overall, the authors concluded that further investigations were needed to evaluate whether the low-cost colorimeters could be effective across various environments including field conditions. Other authors have investigated the potential for using smart-phone cameras (in conjunction with soil colour apps) to assess soil colour (e.g. Gomez-Robledo *et al.*, 2013, de Castro Raulino *et al*., 2021). They concluded that

smart phone cameras had potential for determining soil colour although the accuracy of the results was affected by in-field conditions (they performed best in bright light).

- Researchers have also assessed the potential for quantitative indexes of soil drainage, inferred from soil colour and/or gley features. For example, Evans and Franzmeier (1988) used numeric indexing of Munsell notation, in addition to information regarding mottle characteristics and abundance. Blavet *et al*. (2002) also used Munsell colour notations in addition to a soil redness index (Torrent *et al*., 1983) to derive a continuous index for describing the duration of waterlogging. In addition, Chaplot *et al*. (2000) developed a continuous index (0–100) of soil hydromorphy based on the cumulative thickness of gleyed soil horizons, combined with information regarding the Munsell chroma and value number.

10.4.2 Slowly permeable layer

- To recap, in the ALC, a slowly permeable layer is one through which any excess of water from rainfall drains slowly, because of an adverse combination of texture, structure and porosity. In addition, it must be at least 15 cm thick and begin within 80 cm of the soil surface. The impedance to soil drainage has an important influence on the wetness limitation and provides a key measure of soil drainage characteristics. However, note that on sites with less than 225 FCD (except for soils with a very unstable structure) any slowly permeable layer near the surface can be removed by cultivation. The assumed depth of loosening decreases from 35 cm for sites with ≤200 FCD to 0 at 225 FCD.
- A slowly permeable layer can be identified by its saturated hydraulic conductivity ($K_{sat,}$) which is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient. It is not a rate of water movement rather an indication of the ease with which pores of a saturated soil permit water movement. Soils with high clay content generally have lower hydraulic conductivities than sandy soils because of the predominance of small pores even though sandy soils typically have higher bulk densities and lower total porosities (total pore space) than clay soils.
- Saturated hydraulic conductivity is affected by both soil and fluid properties. It depends on the soil pore geometry as well as the fluid viscosity and density. Although hydraulic conductivity is expressed in velocity units (m/s), it is not a rate. In comparison, permeability or intrinsic permeability is a quantitative property that is controlled solely by pore geometry. It is the soil's hydraulic conductivity after the effect of fluid viscosity and density are removed (USDA, 2004). It is calculated as hydraulic conductivity (K) multiplied by the fluid viscosity divided by fluid density and the gravitational constant.
- Pore geometry and continuity within a soil or landscape vary depending on the direction of measurement. The vertical component of K can be different from the horizontal component.
- Water movement in soil is controlled by two factors: 1) the resistance of the soil matrix to water flow, and 2) the forces acting on each element or unit of soil water. Pore geometry and continuity within a soil or landscape vary depending on the direction of movement and the vertical component of K can be different from the horizontal component.
- Depth to a slowly permeable layer is generally considered a more reliable indicator of soil drainage properties than the presence at a particular depth of gleying. Although gleying is indicative of intermittent waterlogging, it may be an unreliable indicator of the soil water regime

due to the influence of other factors (e.g. presence of organic matter) or because it is a relic feature (Lilly and Matthews, 1994).

- The revised (and unpublished) ALC (MAFF,) also includes identification of a very slowly permeable layer, which is at least 15 cm thick and has all the characteristics described in Table 24, below. It is mainly used in the assessment of disturbed soils and estimation of wetness class is determined using an additional figure, ALC Figure 7b (not shown).

Table 24. Characteristics of a very slowly permeable layer

Structure	either massive or (where texture is medium clay loam or heavier) weakly to moderately developed very coarse prismatic, very coarse platy or very coarse angular blocky; **and**
Soil strength	very firm to extremely firm at field capacity; **and**
Porosity	negligible biopores (<0.05% biopores >0.5 mm diameter; **and**
Rooting	no more than few (1-10) very fine to fine fibrous roots and few (1-2) medium to coarse roots per 100 cm^2

11 Final allocation of ALC grade according to wetness limitations

- Once the wetness class (I-VI), texture of the top 25 cm of soil and field capacity days have been determined the ALC grade (1-5) can be allocated.

11.1 Mineral soils

- Table 25, details the ALC grade for mineral soils according to the combination of soil wetness class, soil texture and field capacity days. Broadly, as the soil texture group indicates reduced workability and increased susceptibility to grazing damage the ALC grade is increased, so that for the same wetness class and FCD soils in the first group (i.e. for mineral soils, S, LS, SL and SZL) will have a higher grade than those in the last group (SC, ZC and C). This assumes no other limiting factor is present that may further downgrade (e.g. droughtiness). For example, where the soil wetness class is I and FCD <126, soils in the first group will be ALC Grade 1[9] and those in the fourth group will be ALC Grade 3a (outlined in red in Table 25). Or in another example, where the soil wetness class is II and FCD are 126-150, soils in the first group (i.e. S, LS, SL and SZL) are ALC Grade 1, soils in the second group (ZL, MZCL, MCL and SCL) are ALC Grade 2, in the third group (HZCL and HCL) ALC Grade 3a and in the fourth group (SC, ZC and C) ALC Grade 3b (outlined in red in Table 25).

- Silty clay loam and clay loam are sub-divided into medium (<27% clay) and heavy (27-35% clay); heavier silty clay loams/clay loams are typically less workable than medium soils of the same class. For example, where soil wetness class is I and FCD are <126, a medium clay loam will be ALC Grade 1 whereas a heavy clay loam will be ALC Grade 2.

- For S, LS, SL and SZL soil classes the predominant size of sand fraction may be indicated by the prefix F (fine, more than two thirds of sand <0.2 mm), C (coarse, more than one third of sand >0.6 mm) and M (medium, less than two thirds fine sand and less than one third coarse sand).

[9] However, note that sand is not eligible for Grades 1,2 or 3a and loamy sand is not eligible for Grade 1

- The presence of calcium carbonate in the top 25 cm of a naturally calcareous clayey soil improves soil structure if the climate is not too wet. As a result, the ALC grade is enhanced for naturally calcareous soils (i.e. not derived from liming), with >1% calcium carbonate -$CaCO_3$, 18 to 50% clay in the top 25 cm and ≤150 FCD. This affects SC, ZC or C soil textures in wetness classes I, II and III, HZCL and HCL textures in wetness classes II and III and ZL, MZCL, MCL and SCL texture in wetness class III. For example, a calcareous SC soil with wetness class I and FCD 126-150, will be allocated ALC Grade 2 and a non-calcareous soil ALC Grade 3a (outlined in blue in Table 25, below). The prefix 'calc' is used to identify naturally calcareous soils (containing >1% $CaCO_3$).
- Note that within a wetness class or FCD grouping ALC grade does not always increase/decrease in line with changes in soil group. Also, in general, the ALC grade allocated is not changed by the increase in FCD from 126-150 to 151-175.

Table 25. ALC Table 6. Grade according to soil wetness – mineral soils (Source: MAFF, 1988).

Wetness class	**Texture[1]**	**Field capacity days**				
	Top 25 cm	**<126**	**126-150**	**151-175**	**176-225**	**>225**
I	S[2] LS[3] SL SZL	1	1	1	1	2
	ZL MZCL MCL SCL	1	1	1	2	3a
	HZCL HCL	2	2	2	3a	3b
	SC ZC C	3a (2)	3a (2)	3a	3b	3b
II	S[2] LS[3] SL SZL	1	1	1	2	3a
	ZL MZCL MCL SCL	2	2	2	3a	3b
	HZCL HCL	3a (2)	3a (2)	3a	3a	3b
	SC ZC C	3a (2)	3b (3a)	3b	3b	3b
III	S[2] LS[3] SL SZL	2	2	2	3a	3b
	ZL MZCL MCL SCL	3a (2)	3a (2)	3a	3a	3b
	HZCL HCL	3b (3a)	3b (3a)	3b	3b	4
	SC ZC C	3b (3a)	3b (3a)	3b	4	4
IV	S[2] LS[3] SL SZL	3a	3a	3a	3b	3b
	ZL MZCL MCL SCL	3b	3b	3b	3b	3b
	HZCL HCL	3b	3b	3b	4	4
	SC ZC C	3b	3b	3b	4	5
V	S[2] LS[3] SL SZL	4	4	4	4	4
	ZL MZCL MCL SCL	4	4	4	4	4
	HZCL HCL	4	4	4	4	4
	SC ZC C	4	4	4	4	5
VI		All grade 5				

For naturally calcareous soils with > 1% $CaCO_3$ and 18%-50% clay in the top 25 cm, the grade, where different from that of other soils, is shown *in brackets.* [2]Sand is not eligible for Grades 1, 2 or 3a. [3]Loamy sand is not eligible for Grade 1

11.2 Organo-mineral and peat soils

- Class limits for organo-mineral and peaty textures are defined in Figure 3 of the ALC (Figure 21, below). In the ALC, peat (P) is a soil texture and peaty (PTY) refers to a textural group comprising peat, loamy peat (LP), sandy peat (SP), peaty loam (PL) and peaty sand (PS) (MAFF, 1988). Peat soil has >40 cm of peaty textured material within the 80 cm of the soil profile and organo-mineral or peaty textures present within 30 cm depth. For organo-mineral soils, the texture of the mineral fraction is prefixed by organic or the abbreviation 'org'.

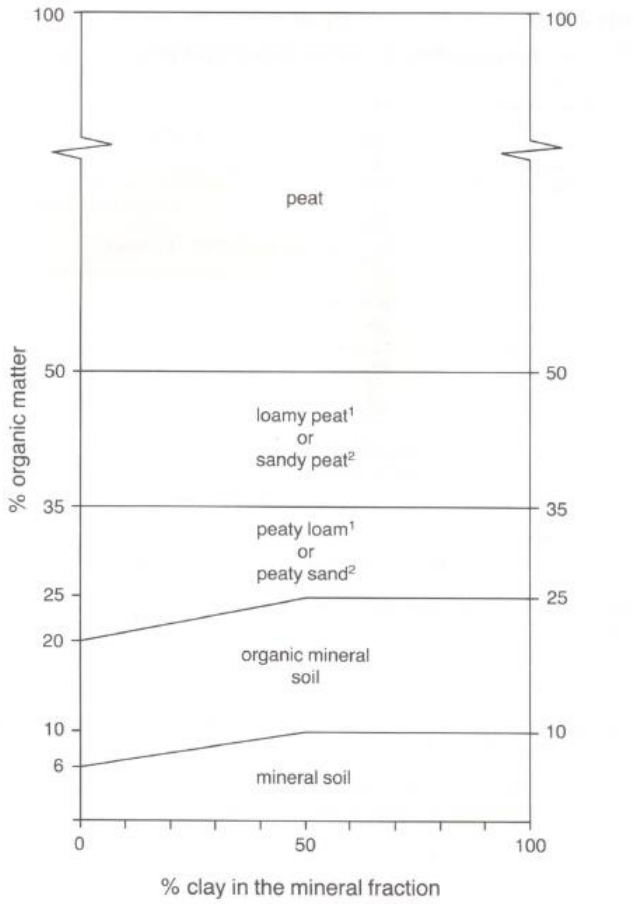


Figure 21. ALC Figure 3, limiting percentage of organic matter and clay for mineral, organic mineral, peaty and peat texture classes. [1]<50% sand in the mineral fraction and [2] ≥50% sand in the mineral fraction (Source: MAFF, 1988).

- Table 26, details the ALC grade for organo-mineral and peaty soils according to the combination of soil wetness class, soil texture and field capacity days. The soil texture groups are the same as for the mineral soils but with an additional group for peaty soils (PTY). It should be noted that for organo-mineral soils, the textural class refers to the mineral fraction of the soil and would be prefixed by the term organic or 'org', e.g. organic clay loam. Also, there are only four FCD groups (i.e. <126, 126-175, 175-225 and >225) compared to five for mineral soils.
- In comparison to the mineral soils ALC grades for organic soils are typically higher for the same combination of wetness class, texture and FCD, particularly in the higher wetness classes. This is because where the climate is dry, organic matter enhances workability even in heavier soils.

However, as the climate becomes wetter organic matter increases water retention and reduces the soil bearing strength.

Table 26. ALC Table 7. Grade according to soil wetness – organo-mineral and peaty[1] soils (Source: MAFF, 1988).

Wetness class	Texture[1]	Field capacity days			
	Top 25 cm	**<126**	**126-175**	**175-225**	**>225**
I	PTY	1	1	1	*
	S LS SL SZL	1	1	1	*
	ZL MZCL MCL SCL	1	1	2	*
	HZCL HCL	1	2	3a	*
	SC ZC C	1	2	3b	*
II	PTY	1	1	1	*
	S LS SL SZL	1	1	2	*
	ZL MZCL MCL SCL	1	1	3a	*
	HZCL HCL	2	2	3a	*
	SC ZC C	2	3a	3b	*
III	PTY	2	2	2	*
	S LS SL SZL	2	2	3a	*
	ZL MZCL MCL SCL	2	2	3a	*
	HZCL HCL	3a	3a	3b	*
	SC ZC C	3a	3a	4	*
IV	PTY	3a	3a	3a	*
	S LS SL SZL	3a	3a	3b	*
	ZL MZCL MCL SCL	3b	3b	3b	*
	HZCL HCL	3b	3b	4	*
	SC ZC C	4	4	4	*
V	PTY	4	4	4	5
	S LS SL SZL	4	4	4	4
	ZL MZCL MCL SCL	4	4	4	4
	HZCL HCL	4	4	4	5
	SC ZC C	5	5	5	5
VI		All grade 5			

[1]Peat and organo-mineral soils as defined by the ALC. *Refers to combinations which do not occur or occur very rarely.

11.3 Conclusions: final grade

- Most ALC surveys will be carried out on undisturbed, non-red mineral soils. However, where the soil is disturbed, red or peaty slight modifications are made to the assessment for wetness class.
- Peaty refers to a soil texture group comprising peat, loamy peat, sandy peat, peaty loam and peaty sand textures. Soils are classified 'peaty' if they contain more than 20% OM (25% OM for soils with more than 50% clay content) or 'organic' if between 6-20% (10-25% for over 50% clay content) of humified organic matter.

- In comparison to the mineral soils ALC grades for organic soils are typically higher for the same combination of wetness class, texture and FCD, particularly in the higher wetness classes. This is because where the climate is dry, organic matter enhances workability even in heavier soils.
- In the ALC five texture groups have been defined according to water retention, workability characteristics and susceptibility to damage by grazing animals; for a given climate Group 1 is the most workable and Group 5 the least (Jones *et al*., 1992). The soil groupings are used in ALC as part of the procedure for allocating the final ALC grade according to soil wetness.
- Some red soils do not exhibit gleying, which may be masked by strong parent material colour, despite having impeded drainage. It is therefore necessary to have a slightly modified procedure for assessing the wetness class of such soils. Red soils are defined as those having one or more horizons within 80 cm of the surface with a Munsell hue of 5YR or redder.
- Soils formed on chalk and limestone usually contain natural calcium carbonate. The presence of calcium carbonate in the top 25 cm of a naturally calcareous clayey soil improves soil structure (calcium binds clay particles together) if the climate is not too wet. As a result, the ALC grade is enhanced for naturally calcareous soils (i.e. not derived from liming), with >1% calcium carbonate -$CaCO_3$, 18 to 50% clay in the top 25 cm and ≤150 FCD. This affects SC, ZC or C soil textures in wetness classes I, II and III, HZCL and HCL textures in wetness classes II and III and ZL, MZCL, MCL and SCL texture in wetness class III. For example, a calcareous SC soil with wetness class I and FCD 126-150, will be allocated ALC Grade 2 and a non-calcareous soil ALC Grade 3a.

12 Assessing soil wetness in other land classification schemes

- Soil wetness is included as a component of many other land capability and suitability assessments, which are reviewed below. For each scheme the methodology for soil wetness assessment is outlined and compared to that used in the ALC.

12.1 USDA soil survey manual

- The United States Department of Agriculture (USDA) Soil Survey Manual was first published in 1937 with subsequent updates in 1951 and 1993; the current version was published in 2017. The USDA soil survey manual describes the major principles and practices needed for making and using soil surveys and is intended primarily for use by soil scientists. It is not a classification of land capability/suitability, but soil surveys (based on the methodology in the manual) provide the information for the USDA land capability system. The system classifies land into eight classes; the risks of soil damage or limitations in use are progressively greater from class I to class VIII (USDA, 1961). The US system has been influential in the development of many land classification systems including the ALC. Indeed, all the land classification systems described below have adopted either explicitly or implicitly components of the US system.
- In the USDA soil survey manual natural drainage class are used to describe the frequency and duration of wet periods under conditions like those under which the soil developed (Table 27). Alteration of the water regime by humans, either through drainage or irrigation, is not considered unless the alterations have significantly changed the morphology of the soil. However, note for land classification purposes where soils can be feasibly improved (e.g. by draining, irrigation etc.) soils are classified according to limitations that remain after the improvements have been carried out (USDA, 1961).

Table 27. USDA natural drainage classes (Source: USDA, 2017).

Class	Description
Excessively drained	Water is removed very rapidly. Internal free water occurrence commonly is very rare or very deep Soils are usually coarse textured and have very high saturated hydraulic conductivity or are very shallow
Somewhat excessively drained	Water is removed from the soil rapidly. Internal free water occurrence commonly is very rare or very deep. Soils are commonly coarse textured and have high saturated hydraulic conductivity or are very shallow
Well drained	Water is removed from the soil readily but not rapidly. Internal free water occurrence commonly is deep or very deep; annual duration is not specified. Water is available to plants throughout most of the growing season in humid regions. Wetness does not inhibit root growth for significant periods during most growing seasons. The soils are mainly free of, or are deep or very deep to, redoximorphic features related to wetness.
Moderately well drained	Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence is commonly moderately deep and transitory through permanent. The soils are wet for only a short time within the rooting depth during the growing season but long enough that most crops are affected. They commonly have a moderately low or lower saturated hydraulic conductivity in a layer within the upper 1 meter, periodically receive high rainfall, or both.
Somewhat poorly drained	Water is removed slowly so that the soil is wet at a shallow depth for significant periods during the growing season. Internal free water occurrence is commonly shallow to moderately deep and transitory to permanent. Wetness markedly restricts the growth of crops, unless artificially drained. Soils usually have one or more of the following characteristics: low or very low saturated hydraulic conductivity, a high water table, additional water from seepage, or nearly continuous rainfall.
Poorly drained	Water is removed so slowly that the soil is wet at shallow depths periodically during the growing season or remains wet for long periods. Internal free water occurrence is shallow or very shallow and common or persistent. Free water is commonly at or near the surface long enough during the growing season that most crops cannot be grown, unless artificially drained. The soil, however, is not continuously wet directly below plough depth. Free water at shallow depth is common. The water table is commonly the result of low or very low saturated hydraulic conductivity, nearly continuous rainfall, or a combination of these.
Very poorly drained	Water is removed from the soil so slowly that free water remains at or very near the surface during much of the growing season. Internal free water occurrence is very shallow and persistent or permanent. Unless the soil is artificially drained, most crops cannot be grown. The soils are commonly level or depressed and frequently ponded. In areas where rainfall is high or nearly continuous, slope gradients may be greater.

- The USDA soil survey manual also gives guidance on the assessment of free soil water (i.e. water that moves through the soil under gravity). Table 28 gives the classes and criteria used to describe soil water regimes. The classes indicate thickness of perched water layer, depth to the upper boundary and aggregate time of occurrence.

Table 28. USDA Classes of internal free water (Source: USDA, 2017).

Classes	**Criteria**
Thickness if perched	
Extremely thin	<10 cm
Very thin	10 cm to <30 cm
Thin	30 cm to <100 cm
Thick	>100 cm
Depth	
Very shallow	<25 cm
Shallow	25 cm to <50 cm
Moderately deep	50 cm to <100 cm
Deep	100 cm to <150 cm
Very deep	>150 cm
Cumulative annual pattern	
Absent	Not observed
Very transitory	Present <1 month
Transitory	Present 1 to 3 months
Common	Present 4 to 6 months
Persistent	Present 7 to 12 months
Permanent	Present continuously

- The US Soil Survey Manual suggests a method for approximating K_{sat} class based on soil texture and bulk density. The bulk density of a particular soil horizon is estimated for a given texture using Figure 22. For example, in Figure 22a, a clay loam with 35% sand and 35% clay and a bulk density of 1.20 g/cm^3 has a low bulk density class (located between the iso-bulk density lines of 1.06 and 1.33 g/cm^3 ; the red lines on Figure 22a connecting points having the same bulk density). The textural triangle in Figure 22b that corresponds with the bulk density class determined from Figure 22a is then used to determine indicative K_{sat} class. The K_{sat} class is “moderately high” for the clay loam in the low bulk density class (1 to 10 µm/s).
- Note, saturated hydraulic conductivity is one of the most variable soil properties as it is determined by total porosity, pore-size distribution, and tortuosity of flow paths, all of which are highly affected by land use and management (USDA, 2017). Consequently, where definitive values of K_{sat} are required, these should be determined using on site measurements.

12.1.1 Comparison with ALC

- There are no wetness classes in the USDA guidance, which uses natural drainage classes instead. Prior to the current version (MAFF, 1988) the ALC also used soil drainage classes to assess soil wetness. These used the same categories as the USDA drainage classes (in Table 27) but omitted the ‘somewhat rapidly (excessively) drained’ class. Soil wetness classes were first introduced in the 1974 edition of the SSEW Field Handbook, which included six wetness classes based on depth/duration of soil wetness. This recognised that soil wetness state was more than just profile morphology (e.g. gleying) but related to periodicity of water in the rooting zone which is a combination of factors such as texture, structure and relationship with climate. Soil wetness classes were subsequently developed by Hodgson and Avery (1985) into the classes that appear in the current ALC guidelines (MAFF, 1988).

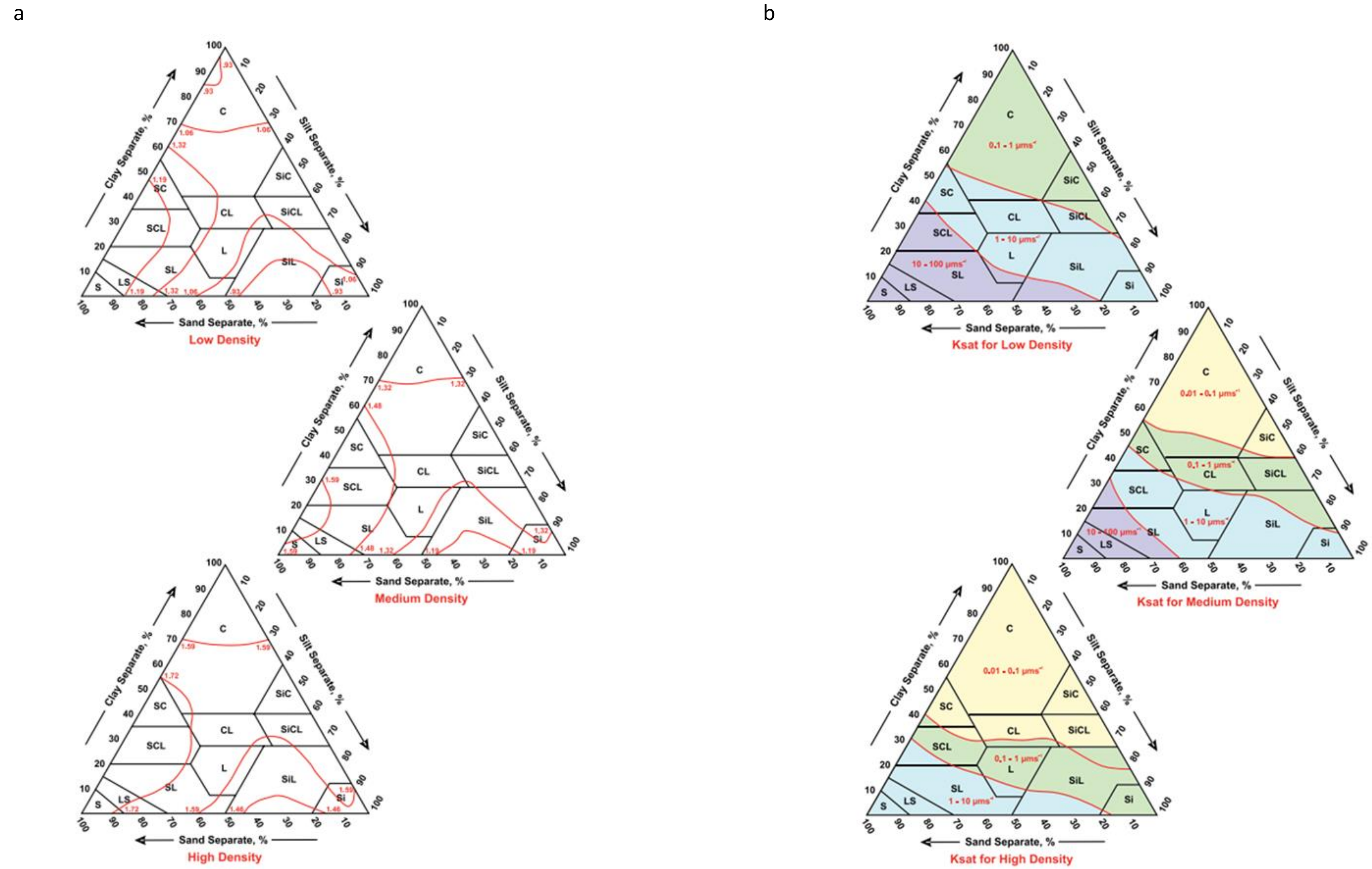


Figure 22. Saturated hydraulic conductivity classes calculated from a) bulk density and b) texture relationships. Colours indicate classes of saturated hydraulic conductivity, e.g., yellow shaded areas indicate the low saturated hydraulic conductivity class, i.e., K_{sat} 0.01-0.1 µm/s. (Source: USDA, 2017).

12.2 USDA Hydrologic soil groups

- USDA soil scientists and engineers used a collaborative approach to develop a model for classifying four hydrologic soil groups (USDA, 2009). Hydrologic soil group is determined by the water transmitting soil layer with the lowest saturated hydraulic conductivity and the depth to any layer that is essentially water impermeable or depth to a water table (if present). The least transmissive layer can be any soil horizon that transmits water at a slower rate relative to those horizons above or below it. The groupings are based on the premise that soils found within a climatic region that are similar in depth to a restrictive layer or water table, transmission rate of water, texture, structure, and degree of swelling when saturated, will have similar runoff responses. The classes are based on the following factors:
    - Intake and transmission of water under the conditions of maximum yearly wetness
    - Soil not frozen
    - Bare soil surface
    - Maximum swelling of expansive clays
- In the USDA system an impermeable or nearly impermeable layer has a saturated hydraulic conductivity (K_{sat}) ranging from 0 µm/s to 0.9 µm/s. Table 29, below illustrates the criteria used to allocate a soil to hydrologic soil groups (HSG) according to the depth to an impermeable layer (soil or bedrock), depth to high water table and the K_{sat} of the least transmissive layer in the depth range. Where this data is unavailable or unreliable, USDA guidance suggests that other soil properties such as texture, compaction (bulk density), strength of soil structure, clay mineralogy, and organic matter are used to estimate the rate of water movement.
- Soil textural groups typically associated with each HSG are given in Table 30, below.

12.2.1 Comparison with ALC

- This method has similarities with ALC as it is based on the depth to a slowly permeable layer and on broad textural soil groups. The hydrologic groupings according to soil texture are in line with those used in ALC Tables 6 and 7 to allocate ALC grade according to soil wetness. Also, the nearly impermeable layer is defined as having a K_{sat} of 0.9 µm/s (equating to c.8 cm/day) which is in line with the K_{sat} of 10 cm/day used to define a slowly permeable layer in the ALC.

Table 29. Criteria used to allocate a soil to a hydrologic soil group (HSG) (Source: USDA, 2009).

Depth to water impermeable layer[1]	Depth to high water table[2]	K_{sat} of least transmissive layer in depth range	K_{sat} depth range	HSG[3]
<50 cm	~	~	~	A
50 to 100 cm	<60 cm	>40 µm/s	0-60 cm	A/D
		>10 to ≤40 µm/s		B/D
		>1 to ≤10 µm/s		C/D
		≤1 µm/s		D
	>60 cm	>40 µm/s	0-50 cm	A
		>10 to ≤40 µm/s		B
		>1 to ≤10 µm/s		C
		≤1 µm/s		D
>100 cm	<60 cm	>10 µm/s	0-100 cm	A/D
		>4 to ≤10 µm/s		B/D
		>0.4 to ≤4 µm/s		C/D
		≤0.4 µm/s		D
	60 to 100 cm	>40 µm/s	0 to 50 cm	A
		>10 to ≤40 µm/s		B
		>1 to ≤10 µm/s		C
		≤1 µm/s		D
	>100 cm	>10 µm/s	0 to 100 cm	A
		>4 to ≤10 µm/s		B
		>0.4 to ≤4 µm/s		C
		≤0.4 µm/s		D

[1]An impermeable layer has a K_{sat} less than 0.01 µm/s or a component restriction related to soil type or bedrock. [2]High water table during any month during the year. [3]Dual hydrologic soil groups (HSG) classes are applied only for wet soils (water table less than 60 cm). If these soils can be drained, a less restrictive HSG can be assigned, depending on the K_{sat}.

Table 30. Water transmission and soil texture characteristics of soil hydrologic groups (Source: USDA, 2009).

Group	Water transmission	Soil texture	Notes
A	Free	<10% clay. >90% sand Texture class: S	LS, SL, ZL may be in this group if they are well aggregated, have low bulk density and >35% rock fragments
B	Unimpeded	10-20% clay. 50-90% sand Texture class: LS, SL	ZL, SZL, SCL or ZCL may be in this group if they are well aggregated, have low bulk density and >35% rock fragments
C	Somewhat restricted	20-40% clay. <50% sand Texture class: SZL, ZL, ZCL, CL, SCL.	C, ZC, SCL may be in this group if they are well aggregated, have low bulk density and >35% rock fragments
D	Restricted or very restricted	>40% clay. <50% sand Texture class: C, ZC, SC	May have high shrink/swell potential
Dual group	Where soil in class D can be adequately drained, they are assigned to dual groups (A/D, B/D and C/D). Adequately drained means that the seasonal water table is kept at least 60 cm below the soil surface (where it would be higher in a natural state).		

12.3 Land capability classification for agriculture (Scotland): soil wetness

- The land capability classification for agriculture (LCA) was designed to compile detailed information on soil, climate and relief in a form that would be of value to land use planners, agricultural advisers, farmers and other land managers (Bibby *et al*., 1991). It ranks land based on its potential productivity and cropping flexibility determined by the extent to which its physical characteristics impose long term restrictions on agricultural use.
- The LCA assessment is based on the premise that the most widespread effect of the wetness limitation is on land management (i.e. workability, trafficability and poaching risk) rather than direct effects on the growing plant. There are three main parts to the assessment:
    - Soil wetness class and depth to impermeable horizon
    - Water retention, plasticity, and strength properties of the topsoil (soil texture and organic matter content) and
    - The climate (field capacity days)
- For land classification purposes the aim is to assess the remaining limitations after appropriate measures have been put in place to alleviate wetness and workability problems (e.g. field drains). The LCA includes six soil wetness classes (Table 31), with I the driest and VI the wettest; the classes are based on the presence/absence of gley features and/or an impermeable horizon within 80 cm depth.

Table 31. LCA soil wetness class (Source: Bibby *et al.,* 1991).

Wetness class	Description
I	The profile normally lacks gley features* within 70 cm or an impermeable horizon within 80 cm depth. Many strongly gleyed, permeable soils, with efficient drainage systems also occur in this class.
II	The profile normally lacks gley features within 40 cm or an impermeable horizon within 60 cm depth
III	The profile normally lacks gley features or an impermeable horizon within 40 cm depth
IV	The profile normally has gley features and an impermeable horizon within 40 cm depth, but lacks a humose or peaty topsoil greater than 20 cm thick
V	The profile normally has prominent gley features within 40 cm depth and is usually wet within 70 cm depth. Commonly the topsoil is humose or peaty and the natural vegetation has numerous hydrophilous[10] species
VI	The profile normally has a peaty topsoil, a prominently gleyed mineral subsoil and is usually wet within 40 cm depth. The natural vegetation consists predominantly of hydrophilous species

*Defined as greyish soil colours with associated ochreous mottling resulting from reduction and mobilisation of iron compounds under anaerobic conditions.

- The LCA defines impermeable horizons as subsurface horizons at least 15 cm thick and with an upper boundary within 80 cm depth. Bibby *et al*. (1991) note that the most precise physical definition of an impermeable horizon is that it has a horizontal saturated hydraulic conductivity (K_s) of less than 10 cm/day. Note that although the terminology is different in the LCA

[10] Species growing in or near water

(impermeable horizon) and the ALC (slowly permeable layer) these features are essentially the same. Morphological criteria are also defined which can be used where measurements of K_s are not practical; all four criteria A-D must be met to define an impermeable layer (Table 32). However, where B, C or D are imprecise supplementary criteria may be used to define an impermeable layer.

Table 32. LCCA morphological criteria for impermeable horizons (Source: Bibby *et al*., 1991).

	Description
A	particle size classes finer than sandy loam
B	massive, platy or prismatic structure: weak, moderate or strongly developed coarse angular blocky structures; weakly developed fine or medium angular blocky structures
C	moderately firm, or firmer ped strength when moist
D	few, or widely spaced (<0.5%) visible pores

- The method to assess soil related components of the limitation are based on the relationship between soil texture and retained water capacity. Topsoil retained water capacity is defined as the volume of water held by an undisturbed core sample equilibrated at 0.05 bar suction (Hall *et al*., 1977). Bibby *et al.* (1991) define three classes for mineral soils for this property, i.e. low: <35%, medium: 35-45% and high: >45% based on broad groupings of soil textural, Table 33, below. Note, that the textural classes are those defined by the USDA not those used in the ALC.
- The wetness class, depth to impermeable horizon and retained water capacity are used to allocate a grade from 'a' to 'f' according to workability and trafficability (for arable land, Table 34) or trafficability and poaching risk (grassland, Table 36). For example, arable mineral soils in wetness class I with an impermeable horizon >80 cm are grade 'a' whereas mineral soils in wetness class IV with an impermeable horizon at the same depth are grade 'c' or 'd' (depending on the retained water capacity).
- The class allocated in the soil assessment (i.e. a-f) is then used in conjunction with median field capacity days (<125, 125-150, 150-175, 175-200 and >200 days) to allocate the final class according to soil wetness, Table 35. For example, where the soil assessment result is grade 'a' the capability class ranges from 1-2, depending on the number of field capacity days. In comparison, where the soil assessment is grade 'f' the capability class ranges from 3-6.

Table 33. LCA retained water capacity according to soil texture (Source: Bibby *et al*., 1991).

Retained water capacity (% volume)	Soil texture
High >45%	Peaty and humose soils Clay, silty clay, sandy clay Part: clay loam, silty clay loam
Medium 35-45%	Loam, silt loam, silt, sandy clay loam Part: clay loam, silty clay loam
Low <35%	Sandy loam, loamy sand, sand

Table 34. LCA soil assessments for workability and trafficabilty for arable soils (Source: Bibby *et al.*, 1991).

Wetness class	Depth to impermeable horizon (cm)	Retained water capacity of topsoil mineral soils			Humose or peaty soils
		Low	Medium	High	
I	>80	a	a	a	a
II	>80	a	a	b	a
	40-80	b	b	c	b
III	>80	b	c	c	b
	40-80	c	c	d	c
	<40	c	d	d	d
IV	>80	c	d	d	d
	40-80	c	d	d	e
	<40	d	e	e	f
V	>80	d	e	e	f
	40-80	e	f	f	f
	<40	e	f	f	f
VI	All depths	f	f	f	f

Table 35. LCA climate and soil assessments giving capability class (Source: Bibby *et al.*, 1991).

Climatic assessment	Soil assessment					
Median field capacity days	a	b	c	d	e	f
	Class limits					
<125	1	1	2	3	3	3
125-150	1	2	3	3	3	4
150-175	1	2	3	3	4	4
175-200	2	3	3	4	4	5
>200	2	3	3	4	5	6

Table 36. LCA estimation of grassland trafficability and poaching risk (Source: Bibby *et al.*, 1991).

Wetness class	Depth to impermeable horizon (cm)	Climate							
		Max PSMD >100 mm				Max PSMD <100 mm			
		Retained water capacity				Retained water capacity			
		Low	Medium	High	Peat	Low	Medium	High	Peat
I and II	>80	a	a	a	a	a	b	b	c
	80-40	a	a	b	b	b	b	c	d
	<40	a	a	b	-	b	b	c	-
III and IV	>80	a	b	b	c	c	c	c	f
	80-40	b	b	c	d	c	c	d	f
	<40	c	c	d	-	d	d	e	-
V and VI	>80	d	d	e	e	e	e	e	f
	80-40	e	e	e	e	e	e	e	f
	<40	e	e	e	-	e	e	e	-

12.3.1 Comparison with ALC

- The process of allocating a soil to a wetness class is more detailed in the ALC than in the LCA. Where quantitative data is not available for the duration of waterlogging the ALC class is allocated according to ALC Tables 12 and 13 and ALC Figures 6 to 8, which include reference to field capacity days, depth to gleying and subsoil texture. In the LCA, soil wetness class is allocated according to a single Table.
- The ALC includes the identification of a slowly permeable horizon, whereas the LCA includes the identification of an impermeable horizon. Both are defined as at least 15 cm thick with an upper boundary within 80 cm of the surface. The LCA includes a precise definition of an impermeable horizon (based on hydraulic conductivity of <10 cm per day) whereas the 1988 ALC Guidelines do not quantitively define the slowly permeable horizon. However, note that Avery (1980) defined a slowly permeable layer as a layer with a lateral saturated conductivity of <10 cm per day suggesting that the terms impermeable and slowly permeable are used interchangeably in some cases. Both the ALC and LCA include broadly (although not exactly) similar morphological criteria for identifying the permeable/slowly permeable horizons, based on soil texture, structure and ped strength.
- Both systems require the identification of gleying, either a gleyed horizon (ALC) or gleyed features (LCA), however, the ALC has much more detail on the precise characteristics of a gleyed soil.
- The ALC divides mineral soil texture classes into four groups according to ease of cultivation and susceptibility to damage by grazing animals. In comparison, the LCA soil texture grouping is based on retained water capacity (low, medium and high). Soils with low retained water capacity (in the LCA) correspond to those in the ALC that are the most workable; those with high retained water capacity, correspond to those in the ALC that are in groups 3 and 4 for workability (i.e., the least workable)
- The LCA uses wetness class, depth to impermeable horizon and retained water capacity to assess workability and trafficability (or poaching risk for grassland). In comparison, there is no explicit consideration of workability in the ALC.
- Both systems categorise FCD into five groups to represent the climate in dry (<125/<126) to wet areas (>200/>225) and as part of the final grade allocation process.

12.4 New Zealand Land Use Capability-LUC (Lynn et al., 2009).

- The Land Use Capability (LUC) system has been used in New Zealand since 1952 and was designed to produce national standards, which were used as the basis for the government's financial assistance to farmers for erosion control. Currently it is used as the basis for planning and supporting sustainable land use at the farm, district, regional and national level (Lynn *et al*., 2009). It assesses the general capability of land for productive use or uses rather than its suitability for specific land uses or crops.
- The LUC has three components: LUC class (assessment of the land's capability for use while considering its physical limitations, i.e. rock type, soil, slope angle, erosion type/severity and vegetation cover), LUC subclass (identifies the main kind of limit or hazard, i.e. erodibility, wetness, soil or climate) and LUC Unit (groups together land which requires the same kind of management), Figure 23. Similarly, to the ALC, the grade is allocated according to the most

limiting factor. LUC class 1 is suitable for a wide range of land uses and has the least limitations to use, whereas LUC class 8 has the most limitations and is typically managed for conservation, biodiversity or catchment management.

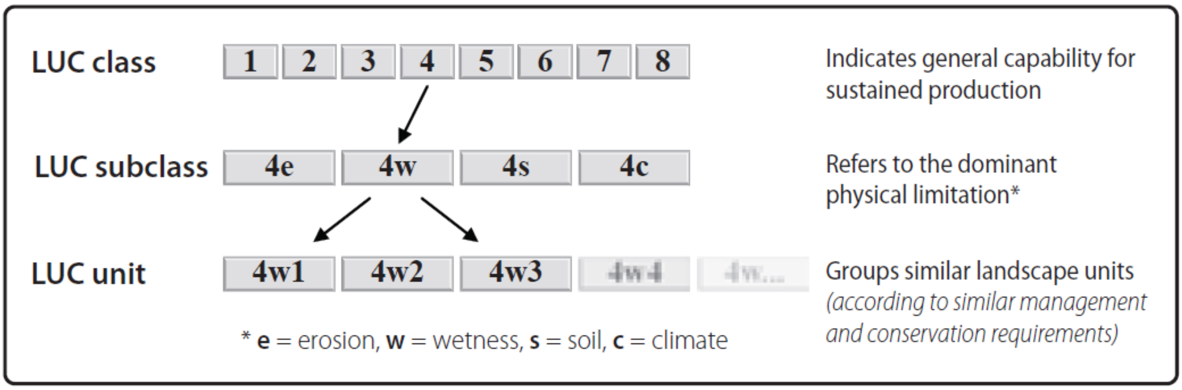


Figure 23. Schematic of the New Zealand Land Use Capability classifications (Source: Lynn et al., 2009).

- The LUC assumes that permanent physical limitations of the land remain, rectifiable limitations can be removed, above average land management is practised. For rectifiable limitations land is assessed as if the limitation has already been removed (e.g. drainage has been installed).
- In the LUC soil wetness defined as 'either a high water table, slow internal drainage and/or frequent flooding or ponding from streams or coastal water' is assessed by visual examination of the site and soil profile, in particular, hydromorphic features and accumulated water.

The presence or absence of hydromorphic features are associated with oxygen availability. The LUC describes these as 'gleying (grey-coloured horizons caused by extended periods of waterlogging), mottling (brown, yellow or orange patches that suggest a seasonal water table and pale horizons associated with perched water tables (sitting on an iron or clay pan)'. The second feature considered by the ALC is the presence or absence of accumulated water either as a water table at depth or as free-standing water (e.g. ponding). Water accumulation can be seasonal and the LUC notes that is should be assessed in conjunction with hydromorphic features.

- Table 37, shows an example relationship between wetness subclasses and depth to hydromorphic features, albeit that regional variations will occur.

12.4.1 Comparison with ALC

- The New Zealand LUC system includes wetness as one of the four main physical limitations which are considered to limit land use capability. There are no specific limits or definitions for the wetness subclasses, and it is recognised that there will be regional variations. The LUC does not explicitly consider climate or soil texture as part of the assessment of soil wetness. This is probably a reflection of the fact that the LUC is designed to assess the general capability of land for productive use rather than its suitability for specific land uses or crops.

Table 37. Example relationship between the wetness subclass and depth to hydromorphic features, water table depth, and the presence of standing water (Source: Lynn et al., 2009).

LUC subclass	Depth to hydromorphic* feature (cm)	Water table depth and standing water
1w	>90 cm	Not applicable
2w	45-90 cm	Seasonally high water table**
3w	45-90 cm	Moderately high water table (for 0.5 year)
4w	<45 cm	Moderately high water table (for 0.5 year)
5w	<45 cm	High water table. Limited standing water
6w	<30-45 cm	Water table at or within 30 cm. Standing water
7w	<30 cm	Significant standing water
8w	<30 cm	Extensive standing water

*Hydromorphic features: low chroma colours, gleying or mottling. **High water table, at or within >45 cm of the ground surface.

12.5 New Zealand Manual of land characteristics for evaluation of rural land

- Webb and Wilson (1995) noted that whilst the LUC system provides a good, generalised assessment of land versatility it had limited precision when assessing specialist or intensive land uses. In addition, they noted that some soil criteria are poorly defined. As a result, the authors defined a set of critical values that could be used to define class limits, ranging from 1 (very good) to 7 (very poor). Soil wetness was expressed as the duration of wetness within specified depths in most years and 'wet' soil was defined as soil containing water held at a tension of <1 kPa (Table 38).

Table 38. Wetness status based on days of wetness occurring within different soil depth increments (Source: Webb and Wilson, 1995).

Days of wetness with depth increments (metres)			Description	Rating
0-0.45	0.45-0.9	0.9-1.2		
0	0	<30	Nil	1
0	<30	Any	Minimal	2
<30	30-90	Any	Very low	3
30-90	90-180	Any	Low	4
90-180	180-300	Any	Moderate	5
180-300	>300	Any	High	6
>300	Any	Any	Very high	7

- Webb and Wilson (1995) suggested that the duration of anaerobic conditions could be estimated from seasonal observations of the soil at various depths (Table 39). Also, that soil moisture could be inferred from morphological indicators of reduction. The authors also noted that low chroma colour percentages were often reliable indicators of reduced and oxygen deficient conditions where the colour is not historic. Where a causal relationship with wetness or reduction could be shown Webb and Wilson (1995) suggested the groupings according to wetness show in Table 40.

Table 39. Wetness status based on days with reduced soil conditions within specified percentages of soil mass occurring within different soil depth increments (Source: Webb and Wilson, 1995).

Days with reduced conditions and % of soil mass reduced by depth (metres)							
0-0.45		0.45-0.9		0.9-1.2		Wetness	Rating
Days	Soil mass (%)	Days	Soil mass (%)	Days	Soil mass (%)		
0	0	0	0	<30	<5	Nil	1
0	0	<30	<5	Any	Any	Minimal	2
<30	<50	30-90	<5	Any	Any	Very low	3
30-90	<20	90-180	<20	Any	Any	Low	4
90-180	>20	180-300	>20	Any	Any	Moderate	5
180-300	>20	>300	>20	Any	Any	High	6
>300	>20	Any	Any	Any	Any	Very high	7

Table 40 Wetness status based on mottle pattern and/or drainage class. The table is used as a key, beginning at the top. Criteria for both high- and low-chroma mottles must be true within any depth increment (Source: Webb and Wilson, 1995).

Percentage occurrence of mottles by depth increments (metres)								
0-0.45		0.45-0.9		0.9-1.2		Wetness	Drainage class	Rating
High chroma mottles[1]	Low chroma mottles[2]	High chroma mottles	Low chroma mottles	High chroma mottles	Low chroma mottles			
0	0	0	0	<2	0	Nil	Well drained	1
0	0	<2	0	Any	Any	Minimal	Well drained	2
1-10	0	≥2	<50	Any	≥50	Very low	Moderate	3
≥2	1-10	Any	≥50	Any	Any	Low	Imperfect	4
≥2	10-50	Any	≥50	Any	Any	Moderate	Imperfect to poor	5
Any	≥50	Any	Any	Any	Any	High	Poor	6
<2	≥85	Any	Any	Any	Any	Very high	Very poor[3]	7

[1] High-chroma mottles are any mottle with higher chroma than the soil matrix.
[2] Low-chroma mottles have moist chroma of 2 or less, or moist chroma of 3 with a value of 6 or more.
[3] Requires an organic topsoil (Clayden and Hewitt, 1989 cited by Webb and Wilson, 1985).

12.5.1 Comparison with ALC

- The soil wetness rating system designed by Webb and Wilson (1985) has some similarities to the ALC, considering the duration of waterlogging and the gleyed features of the soil. It does not explicitly consider climate or soil texture as part of the soil wetness assessment.

12.6 Guidelines for the classification of agricultural land in Tasmania (Grose, 1999).

- The Tasmanian system defines land capability as '*a ranking of the ability of land to sustain a range of agricultural uses without degradation of the land resource*'. It provides a series of guidelines for the quantitative assessment of land capability and supports a consistent approach to land evaluation in the State. It is used to inform strategic planning by local councils and provide an effective base for land use planning. It is based on the New Zealand system where land is allocated a class (giving a general indication of the limit to use), subclass (identifying the dominant limitation) and unit (grouping together similar types of land).
- The classification system in Tasmania is based primarily upon three permanent biophysical features of the landscape - soil, slope and climate, and their interactions. Two types of wetness limitation are defined, 1) wetness from restricted internal drainage and 2) wetness from flooding. The former is relevant for this report. In line with many other land capability systems where it is feasible to modify limitations (i.e. improve land drainage) land is assessed assuming the improvements have been made.
- Drainage status is defined according to the depth and degree of mottling (Table 41). Drainage status is further described in Table 42, below; drainage classes are comparable to those used in the US system. The guidance emphasises that care needs to be taken to ensure that the mottles are truly redox mottles (not a weathering product of rocks and stones within the profile or mixing of material from adjacent horizons) and that they are a contemporary feature. In addition, it is noted that the assessment of soil drainage remains a somewhat subjective procedure and that some experience is necessary for consistent and reliable results.

Table 41. Tasmania land class specifications for soil wetness (Source: Grose, 1999).

Land class	Drainage status	Mottle depth (cm)	Mottle severity	Approximate permeability (mm/day)	Comments
1	Well	>90	Few/faint	250-500	
2	Well Rapidly	>90 Nil	Few/faint Nil	250-500 >500	 Sandy soils
3	Moderately well	50-90	Few/distinct	50-250	
4	Imperfectly	20-50	Common/faint	25-50	May have few rusty root mottles to surface; possible seasonal water table below 50 cm
5	Poorly	10-20	Common/distinct	5-25	May be rusty root mottles from surface; may have shallow seasonal groundwater table
6	Very poorly	Surface	Many/prominent	5	May be saturated for long periods or have shallow groundwater table
7	Swamp	Many/gleyed			Permanently saturated

Table 42. Tasmanian guidelines for soil drainage (Source: Grose, 1999).

Drainage status	Definition	Capability class
Rapidly drained	Soils are usually coarse-textured; no horizon is normally wet for more than several hours after water addition.	1 or 2
Well drained	Soils often of medium texture; some horizons may remain wet for several days after water addition.	1 or 2
Moderately well drained	Soils are usually medium to fine textured: some horizons may remain wet for as long as a week after water addition	3
Imperfectly drained	Soils have a wide range of texture: some horizons may remain wet for periods of several months.	4
Poorly drained	Soils have a wide range of texture: all horizons may remain wet for periods of several weeks.	5
Very poorly drained	Soils have a wide range of texture: strong gleying and surface accumulation of organic matter are typical.	6

12.6.1 Comparison with ALC

- The Tasmanian system is much less detailed than the ALC although it does consider many of the same factors (e.g. soil texture and structure (via soil permeability) and gleying (soil mottles).

12.7 The Muencheberg Soil Quality Rating (SQR) (Mueller et al., 2007).

- The Muencheberg SQR is a method for detecting and assessing properties and limitations of soils for cropping and grazing (Figure 24). The SQR rating is based on a 100-point scale; classes of SQ are <20 = very poor, 20-40 = Poor, 40-60 = Moderate, 60-80 Good, > 80 = Very good. To calculate the score a series of indicators are ranked from 2 (best condition) to 0 (worst), with possible increments of 0.25 or, more typically 0.5. The final basic score ranges from 0 (theoretical minimum, practical is about 15) to 34. It is a measure of soil quality for farming. Values less than 20 indicate poor soils, values greater than 27 are typical of good soils. A series of hazard indicators are then considered as multipliers for the basic soil score ranging from 0.01 (hazard properties do not allow farming) to 3 (no hazard properties). The lowest multiplier is the valid one (i.e. the most limiting factor).

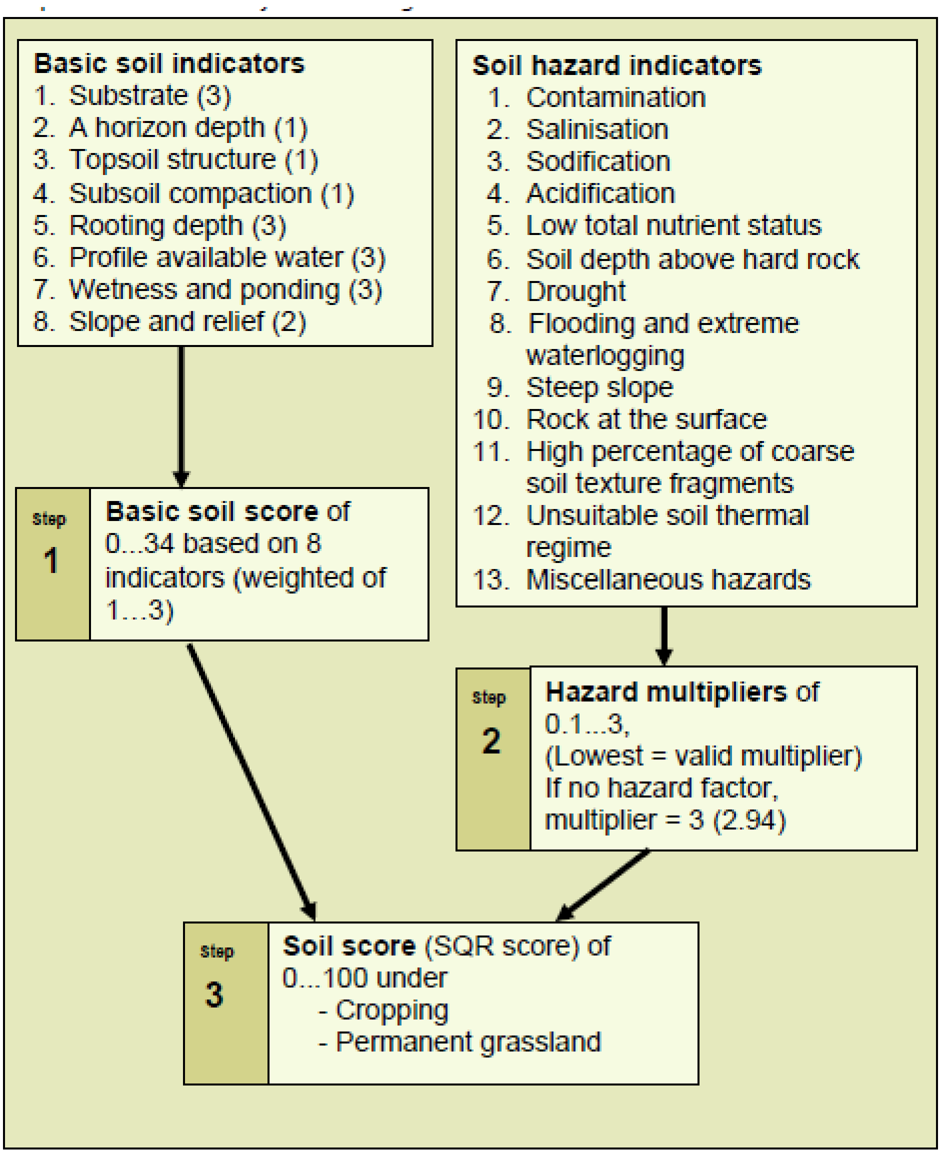


Figure 24. Schematic of the Muencheberg SQR (Source: Mueller et al., 2007).

12.7.1 Soil wetness

- In the SQR wetness and ponding is one of the eight basic soil indicators (Figure 24). The SQR states that '*wetness and ponding (waterlogging) occurs when the soil profile is saturated with water or water appears above the soil and plants lack air. Impeded internal drainage, high and perched water tables are also acknowledged to cause wetness and ponding*'. Soil wetness is scored according to Table 43 below, with additional guidance in Table 44, which uses the USDA drainage classes and the depth to ground or perched water table. The importance of gley features is also acknowledged but cannot be expanded here due to lack of access to the German source publication (Boden, 2005).

Table 43. Scoring of basic indicator wetness and ponding in the SQR (Source: Mueller et al., 2007).

Score	Characteristics	Remarks
2	No surface ponding or wetness	If soil position is in a depression, maximum score = 1.5. If soil suffers from wetness (by suspended water (soils rich in silt and clay or muck) maximum score = 1.5
1.5	Surface ponding extremely rare, temporal wetness in the root zone can occur for shorter periods	
1	Moderate surface ponding up to 3 days after heavy rainfall possible	
0.5	Significant wetness in the root zone for longer periods, moderate ponding	
0	Significant surface ponding and wetness in the root zone can occur for longer than 3 days after heavy rainfall	

Table 44. Guide to wetness and ponding in the SQR (Source: Mueller et al., 2007).

Score	USDA Soil Survey drainage class	Depth of ground or perched water table (m)[1]
2	Well, somewhat excessively, excessively	>1
1.5	Moderately well	0.8-1
1	Somewhat poorly	0.6-0.8
0.5	Poorly	0.5-0.5
0	Very poorly	<0.5

[1]Temperate humid and sub-humid zones, if drainage is impeded by soil structure or indications of additional perched water table, or clear workability limitations, score is reduced by 0.5.

12.7.2 Comparison with ALC

- The SQR acknowledges the importance of soil wetness particularly in terms of the influence on plant growth. It also refers to the effect of numerous days with topsoil water content higher than the plastic limit on soil management (referred to as technological wetness). In contrast to the ALC the assessment of soil wetness is limited and qualitative.

12.8 Canadian land suitability rating system for agricultural crops

- The Canadian land suitability rating system (LSRS) for agricultural crops is a procedure for rating the suitability of land to produce spring seeded small grains and oilseeds in Canada (Pettapiece, 1995). However, it is noted that whilst the system gives a rating for spring-seeded small grains, the underlying procedure can be universally applied and can provide a basic framework for rating the land resource base for any crop.

- The system has two categories: Classes based on the degree of limitation of land for production of the specified crop or crops and subclasses based on the kind of limitation (i.e. climate, soil or landscape related). It is based on a scoring system out of 100, where Class 1 land scores 80-100 and limitations are classed as none to slight to Class 7 land which scores 0-9 (unsuitable). More recently, further work has expanded the LSRS to include crop modules for maize, soybeans, forages (alfalfa, grasses) and canola (Bock *et al*., 2018).

- Soil wetness is considered as part of the subclass soil limitations to identify soils in which excess water limits the production of specified crops. The rating is designed to reflect workability and trafficability conditions. Drainage is used to moderate the soil surface rating for mineral soils (S) and is treated as a percentage reduction to the overall soil score.

- The LSRS considers three main factors, 1) depth to the water table during the critical period (typically spring) over a 20-day period, 2) saturated hydraulic conductivity (i.e. rapid: >15 cm/hour, moderate: 0.5-15 cm/hours and slow: <0.5 cm/hour) and 3) the general climate (i.e. perhumid: growing season precipitation (P)-potential transpiration (PE) less negative than -100 mm, humid: P-PE between -100 and -200 mm and subhumid: P-PE more negative than -200 mm) (Table 45).

Table 45. LSRS percentage reduction to soil score for soil wetness in perhumid, humid and subhumid regions (Source: Pettapiece, 1995).

Depth to water table (cm)	**Drainage class**	**Hydraulic conductivity[1]**								
		Perhumid			**Humid**			**Subhumid**		
		Low	Med	High	Low	Med	High	Low	Med	High
	Standing water	100	100	100	100	100	100	100	100	100
0	Very poor	100	100	100	95	95	95	90	90	90
25	Poor	90	80	75	80	70	65	70	65	60
50	Poor to imperfect	75	60	50	70	50	40	50	40	30
75	Imperfect	60	40	25	45	30	10	30	15	10
100	Imperfect to moderately well	40	20	0	20	10	0	10	0	0
125+	Moderately well to well	20	0	0	10	0	0	0	0	0

[1]Hydraulic conductivity, low: <0.5 cm/hour, medium: 05-15 cm/hour or high: >15 cm/hour

- The LSRS acknowledges that it is not always practical to make the physical measurements necessary to characterise the water regime in line with Table 45. Where these measurements cannot be made soil and vegetation features can be used to estimate the drainage factor; these are detailed in Table 46, below. However, it is noted that these are generalisations, and that expert knowledge is required to undertake these assessments.
- Organic soils are considered separately, and the categorisation is based on the depth to water table, type of organic soil (fibric, mesic or humic) , % fibre >0.15 mm (e.g. 80, 60 or 40% for fibric soil), von Post humification scale (an estimation of the degree of decomposition of peat materials) and hydraulic conductivity (e.g. 50, 15 or 5 cm/hour for fibric soils). As for mineral soils, values (percentage reduction to the overall organic soil score) are tabulated for perhumid, humid and subhumid climates.

Table 46. LSRS factors to estimate drainage where quantitative data is unavailable (Source: Pettapiece, 1995).

Factor to estimate drainage	Comments
Water table	
Water table at or near the surface.	Very poorly drained; Gleysolic soils, in native state.
Water table at 25 to 50 cm	Poorly drained; Gleysolic soils. Prominent (reddish) mottles in the 0 to 50 cm zone.
Water table at 75 cm	Imperfectly drained; usually Gleyed subgroups with prominent mottles in the 50 to 100 cm zone.
Water table at 100 cm	Moderately well and well drained soils; mottling faint or absent.
Tile drains	Assumed to establish water table at 75 cm
Hydraulic conductivity	
Sand	Rapid >15 cm/hour
Load	Medium 0.5-15 cm/hour
Clay	Slow <0.5 cm/hour

12.8.1 Comparison with ALC

Unlike the ALC the LSRS has no specific guidelines on the duration of soil wetness and soil texture is not directly considered as a factor in soil wetness. Instead, the assessment of soil wetness is based on drainage classes, hydraulic conductivity (soil texture can be used as a proxy for this measurement when measured data is not available) and climate categories (rainfall less potential transpiration).

13 Climate extremes or episodic events

- A range of environmental factors can cause significant impact on crop yields and quality. Horticulture Research International (2008) assessed the vulnerability of UK agriculture to extreme climatic events. The authors categorised extreme events as one of two types. Firstly, low probability extreme weather events leading to critical physical and/or physiological thresholds being exceeded during sensitive stages of crop development, resulting in crop failure or significant loss of quality. Extreme weather events would include heat waves, periods of heavy or extended rain, gales or frosts. Secondly, extreme impacts where weather conditions affected crop growth or management resulting in substantial reduction in yield or quality. This could be a consequence of a single event, e.g. late spring frost, or prolonged weather conditions, e.g. warm winters or drier summers. Horticulture Research International (2008) concluded that most important factors affecting crop production were temperature (heat waves, frosts), water (drought, waterlogging) and storms (wind, hail, inundation).

13.1 Extreme events in land quality assessments

- In the assessment of land quality, dynamic variables (e.g. temperature which changes as the season progresses) are converted to static variables (i.e. a single value which stays the same). Hence, a key weakness in using summarised land qualities is that by treating dynamic variables in a static way much of the variability that is an essential property of the land and climate is removed (Hudson and Birnie, 2000). Whilst land evaluation methods based on this approach are of value in land use planning, it is more appropriate for land management decision making to have information on variability from which risk may be assessed (Hudson and Birnie, 2000).

- Previous work investigating changing land capability has focussed on shifts in long-term multi-year averages that are a feature of established classification systems (Brown and Castellazzi, 2014). However, shorter term variability also has a very important role in influencing the relative viability of different land-use systems (Hudson and Birnie 2000). In particular, inter-annual (between year) variability (IAV) is important for agriculture because of the key role of the annual cycle in both planning and management for crop or livestock systems (e.g. Reilly 2002).
- Shorter term variability influences land capability classifications because, although the established classification is based upon a long-term average, the results are sensitive to the period used to define the long-term average (Hudson and Birnie 2000; Brown *et al*. 2008). However, land that is significantly more variable from year to year should intuitively have a lower rating compared to equivalent land with the same average land capability but a more stable annual class (Brown and Castellazzi, 2014). High variability may effectively constrain some land use options due to the higher risks involved, meaning the land is less flexible in its uses. Currently, established classification systems do not incorporate this variability, despite its increasing relevance for adaptive resource management in a changing climate (Brown and Castellazzi, 2014). This probably reflects the fact that most land classification systems are used in long-term planning decisions where stability in grading between years is needed. However, short-term variability is undoubtedly important when assessing land capability and should be considered in any future reviews of the ALC.
- The work of Hudson and Birnie (2000) and Brown and Castellazzi (2014) highlighted the influence of annual changes in weather on LCA climate classes for Scotland. LCA classes for climate are based on the relationship between maximum potential soil moisture deficit (-250 to 0 mm) and accumulated temperature >0°C (up to 2000 day °C). In comparison, ALC classes for climate are based on the relationship between AAR (up to 5000 mm) and AT0 (up to 2000 day °C). Although the two systems use a different indicator of wetness (soil moisture deficit or rainfall) both are based on the principle that a warm dry climate should be graded more highly than a cool wet climate. Consequently, although the precise nature of the effects of episodic or extreme events on land classification will be different in the two systems (LCA and ALC) the overarching trends will be similar.
- As noted, by Brown and Castellazzi (2014) during years of poor weather (i.e. too wet or too dry), climatic constraints will be more important factors than when the weather is good. When the weather is poor it is likely that land classified as ALC Grades 1 or 2 may experience management difficulties more commonly associated with land in lower grades. During years of good weather, the constraints on land capability are likely to be dominated by intrinsic soil properties which will delimit the maximum extent for BMV land despite the favourable weather.
- Climate change predictions suggest that the weather is likely to become more extreme. This suggests that it will be important to consider not just the average climatic conditions when allocating an ALC grade for climate but also the variation around that average. The World Climate Research Programme (WCRP) and WMO expert team on climate change detection and indices have defined a set of 27 core indices which can be derived from land surface observations of daily temperature and precipitation (Table 47). A subset of these indices (highlighted in yellow in Table 47) have been calculated by the Met Office (2018) and could potentially be used as part of the ALC process to attempt to capture the risk of extreme events of relevance to agricultural crops.

Table 47. Climate indices. Yellow highlighted indices were calculated by the Met Office and reported in 'State of the UK climate 2017: Supplementary report on climate extremes'. (Source: Met Office, 2018).

Index	Derived from	Resolution	Description
High temperature			
No of summer days	Daily max temperature	Monthly	No days when the daily max temperature >25°C
No of tropical nights	Daily min temperature	Monthly	No days when the daily min temperature >20°C
Highest max. temperature	Daily max temperature	Monthly	Highest daily max temperature during the month
Highest min. temperature	Daily min temperature	Monthly	Highest daily min temperature during the month
% of warm nights	Daily max temperature	Monthly	% of days when the daily min temperature is >90th percentile centred on a 5-day window for the base period of 1961-1990.
% of warm days	Daily max temperature	Monthly	% of days when the daily max temperature is >90th percentile centred on a 5-day window for the base period of 1961-1990.
Warm spell duration index	Daily max temperature	Monthly	Count of days with ≥6 consecutive days when daily max temperature >90th percentile.
Low temperatures			
No of icing days	Daily max temperature	Monthly	No of days when the daily max temperature is <0°C
No of frost days	Daily min temperature	Monthly	No of days when the daily min temperature is <0°C
Lowest max temperature	Daily max temperature	Monthly	Lowest daily max temperature during the month.
Lowest min temperature	Daily min temperature	Monthly	Lowest daily min temperature during the month
% of cool nights	Daily min temperature	Monthly	% of days when the daily min temperature is <10th percentile centred on a 5-day window for the base period of 1961-1990.
% of cool days	Daily max temperature	Monthly	% of days when the daily max temperature is <10th percentile centred on a 5-day window for the base period of 1961-1990.
Cold spell duration index	Daily min temperature	Monthly	Count of days with ≥6 consecutive days when daily min temperature <10th percentile.
Other temperature			

Index	Derived from	Resolution	Description
Growing season length	Daily mean temperature	Monthly	Count between first span of at least 6 days with mean temperature >5°C and the first span after July 1st of 6 days with mean temperature <5°C
Daily temperature range	Daily max and daily min temperature	Monthly	Average difference between daily max and daily min temperatures
Rainfall indices			
Max. 1-day precipitation	Daily Precipitation	Monthly	Highest value of daily rainfall
Max 5-day precipitation	Daily Precipitation	Monthly	Highest value of rainfall accumulated over 5 days
Simple precipitation intensity index	Daily Precipitation	Monthly	Total precipitation falling on wet days (≥1 mm) divided by no of wet days
Days of rain 1 mm	Daily Precipitation	Monthly	No of days with ≥1 mm rainfall
Days of rain 10 mm	Daily Precipitation	Monthly	No of days with ≥10 mm rainfall
Days of rain 20 mm	Daily Precipitation	Monthly	No of days with ≥20 mm rainfall
Longest dry spell	Daily Precipitation	Annual	Largest number of consecutive days with <1 mm rainfall
Longest wet spell	Daily Precipitation	Annual	Largest number of consecutive days with >1 mm rainfall
Rainfall from very wet days	Daily Precipitation	Annual	Total rainfall falling on days with daily rainfall total >95th percentile of daily rainfall
Rainfall from extremely wet days	Daily Precipitation	Annual	Total rainfall falling on days with daily rainfall total >99th percentile of daily rainfall
Total rainfall	Daily Precipitation	Annual	Annual total rainfall during the year

14 Trafficability and workability assessments

- Modern agriculture relies on machinery to carry out farming operations such as tillage and harvesting. However, one of the potential impacts of regular use of heavy machinery is soil compaction. To help minimize this harmful effect, trafficability (and workability) of agricultural fields needs to be determined (Carranza *et al*., 2019).

- Soil wetness influences the sensitivity of the soil to structural damage and is therefore a major factor in determining the number of days when the soil is in a suitable condition for cultivation (workability), trafficking by machinery or grazing by livestock (MAFF, 1988). Currently the ALC does not directly assess either workability or trafficability but instead considers some of the factors that influence it, i.e. soil wetness and texture.

- Rounsevell (1993) defined trafficability as the ability of soil to support a vehicle while only causing negligible, or reversible, damage. Similarly, Müller *et al*. (2011) defined trafficability as the soil capability to support agricultural traffic without degrading soils and ecosystems. Evaluation of soil trafficability is based on the comparison of stresses applied to the soil and soil strength. Soil strength and deformation depends on both intrinsic properties (soil texture, bulk density, organic matter content) and water content. For any given texture or bulk density, soil strength decreases with increasing moisture content (Müller *et al*., 2011).

- In comparison, workability is defined as the ability of an operation to be executed within predefined limits for damage and performance quality parameters. In the context of tillage, workability is defined as the ability of the soil to produce an adequate friable tilth in preparation for seeding without causing smearing or compaction (Rounsevell, 1993). Or more simply, workability is soil capability to support tillage (Müller *et al*., 2011). Obour *et al*. (2017) outlined the factors that influence soil workability (Figure 25).

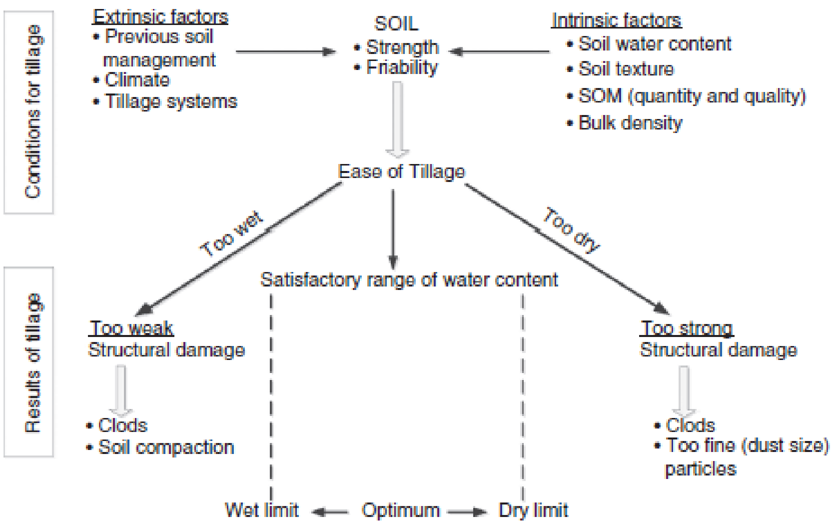


Figure 25. Schematic of the concept of soil workability and factors affecting it (Source: Obour *et al*., 2017).

- Typically, in England fields have a window of opportunity for tillage of a few weeks in autumn and spring (Edwards *et al.*, 2016); opportunities may be even more restricted in Wales or upland England. In practice, suitable conditions for tillage activities have been assessed by farmers based on experience (Obour *et al.* 2017). However, several authors have investigated trafficability and workability threshold levels that could potentially be used to support decision making by farmers.

14.1 Machinery workdays

- Thomasson (1982) defined an empirical model for estimating the number of available workdays for both the spring and autumn tillage periods in England and Wales. This model was subsequently modified by Thomasson and Jones (1989) to assess the sensitivity of workability to variations in climate. The workability model derived machinery workdays (MWD) from climatic factors and soil type for the two seasons when most tillage in England and Wales is performed: spring (1 March-30 April) and autumn (1 September-31 December). The model was developed to determine the variation in MWD over extensive areas by incorporating meteorological and soil survey data.

- The approximate number of MWD in the autumn was calculated as the return date of FC minus 244 (1 September), and in the spring as 120 (30 April)[11] minus the end date for FC. These initial estimates were then adjusted by incorporating an assessment of the soil texture, structure and drainage status based on Table 48, below. This was based on a rating system, ranging from aa for soils best suited to machine operations, to f for soils that are unworkable most of the time (based on soil wetness class and retained water capacity). The soil assessments aa to f were converted into actual days using the soil weightings in Table 49.

Table 48. Soil assessment for adjusting start and end dates of field capacity (Source: Jones, 2010).

Water regime	Wetness class	Depth to slowly permeable layer (cm)	Mineral soils			Humose or peaty soils
			Retained water capacity			
			Low	Medium	High	
1	I	>70 (sandy)	aa	a	a	a
	I	>70	a	a	a	a
1	II	>70	a	ab	b	a
2	II	40-70	b	b	bc	b
2	III	>70	b	c	c	b
		40-70	c	c	cd	c
3	III	<40	c	cd	d	d
3	IV	>70	c	d	d	d
		40-70	c	d	de	e
		<40	d	de	e	f
	V	All depths	e	f	f	f
	VI	All depths	f	f	f	f

[11] Note: 1 September is day 244 and 30 April is day 120 in a typical year (i.e. not a leap year)

Table 49. Soil weightings (days) for adjusting the start and end of field capacity (Source: Thomasson and Jones, 1989).

Soil assessment	Soil adjustments (in days to start and end of field capacity		Total
	Autumn (01/09 to 31/12)	Spring (01/03 to 30/04)	
aa	+30	+20	+50
a	+20	+10	+30
ab	+10	+5	+15
b	0	0	0
bc	-10	-3	-13
c	-20	-5	-25
cd	-25	-8	-33
d	-30	-10	-40
de	-35	-13	-48
e	-40	-15	-55
f	-50	-20	-70

- Thomasson and Jones (1989) mapped MWD (autumn and spring) in England and Wales, using soil and agroclimatic data at 5 km × 5 km resolution (Jones and Thomasson, 1985) from LandIS, which also contained a workability rating for each national soil series, based on the methodology of Table 49. The MWD available for a particular area was represented graphically (Figure 26) and the climatic sensitivity of workability was demonstrated by using the early and late quartile dates for RFC and EFC, which equated to the driest and wettest years in every four.

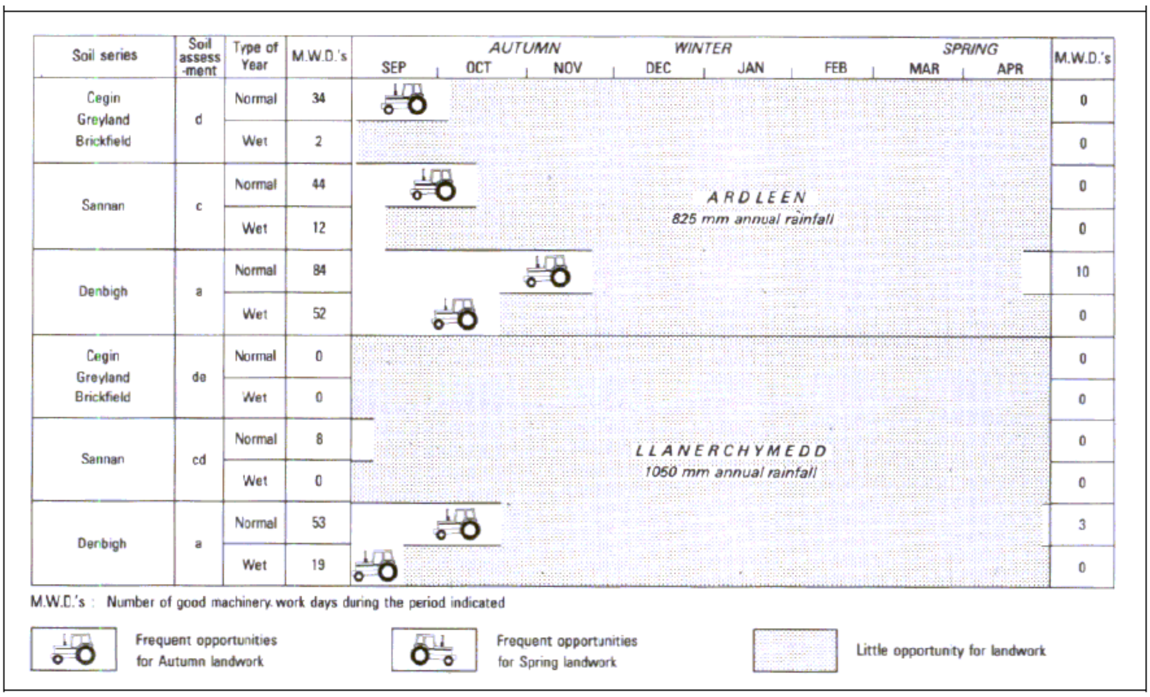


Figure 26. Example machinery workdays for some soil series Wales (wet quartile data) (Source: Thomasson and Jones, 1989).

14.2 Moisture deficit and soil strength

- Earl (1997) developed a technique for estimating the number of trafficable and workable days using historical soil moisture deficit and soil strength data. To collate the data for the model the relationship between soil strength (resistance to cone penetration) under grass ley and winter wheat, and soil moisture deficit was derived over an 18-month period. The data showed a strong correlation between moisture deficit (top 200 mm of the profile) and penetration resistance (R^2 values ranged from 0.60-0.99). This relationship between soil moisture and strength was used to develop a model to predict the number of days a given soil would be trafficable or workable during the year. Trafficable or workable days were those above pre-defined critical limits. Critical limits were determined from qualitative assessments of the field sites (not trafficable, trafficable but not workable, trafficable, and workable) which were related to measured soil moisture deficit. However, as acknowledged by Earl (1997) these relationships were only relevant for the soil types, climatic conditions, and bulk density during the study period.

14.3 Critical moisture content and consistency state

- The way that a soil responds to an applied load or cultivation changes at critical moisture contents or consistency states known as the:
    - Shrinkage limit: below which soil bulk strength is not particularly high (due to lack of water and therefore low surface tension forces and low film cohesion) but clod and aggregate strength is very high (due to attractive forces associated with the clay fraction), and working the soil rearranges clods and aggregates with no structural damage
    - Lower plastic limit: above which clod strength is low and bulk strength is high and soil moisture content is adequate for the water to behave like a lubricant and the risk of structural damage increases with water content
    - Upper plastic limit: above which the soil is in the 'liquid' state, has almost no strength, is readily puddled (compacted) and can be virtually impossible to work.
- Soils are most workable at moisture contents within the friable range between the shrinkage limit and the lower plastic limit, with bulk shear strength increasing and clod shear strength decreasing rapidly with moisture content (Spoor, 1975; Figure 27). At the shrinkage limit end of the friable range, the risk of structural damage is very low, and soil can be cultivated with minimal energy requirement.

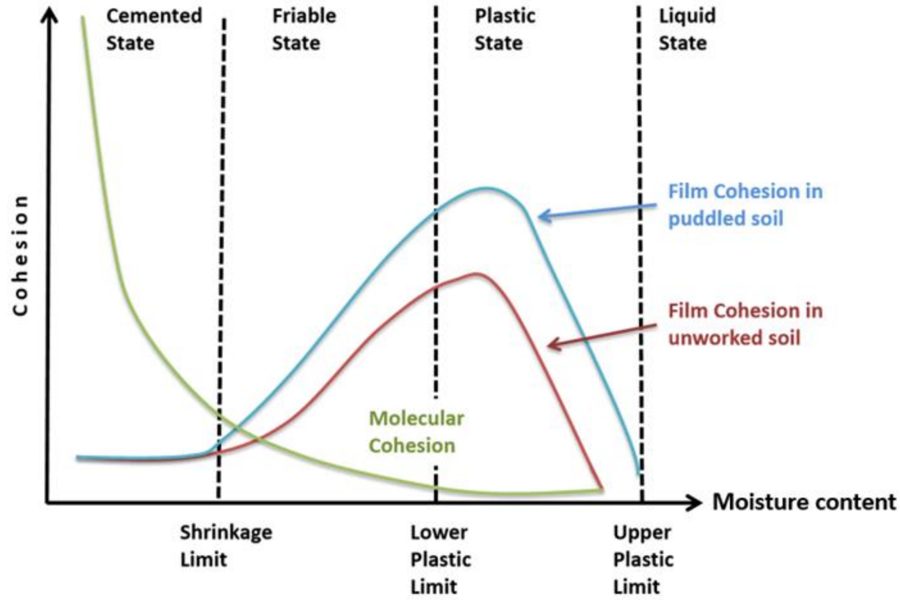


Figure 27. Variation in cohesion with moisture content (Source: Spoor, 1975).

- When soil is in a plastic state (between the lower and upper plastic limits) soil clod and bearing strength declines, resulting in increased wheel slip, rolling resistance and sinkage and compression. The risk of structural damage increases with soil moisture content to a 'sticky point' where bulk shear strength falls and soil sticks to cultivation machinery (Spoor, 1975), resulting in significant:
    - Puddling, the mechanical process whereby wet soil aggregates are disrupted, and some clay is dispersed; and
    - Smearing, localised spreading and smoothing of soil by sliding pressure
- Not all soils have these consistency states. Lighter soils with less than 18% clay content will only reach the lower plastic limit at a relatively high moisture content and the lightest soils will not reach a plastic state or have a 'sticky point' due to lack of clay content and related adhesion forces.
- The risks of soil compaction relate to the load applied and the soil moisture content (relative to the plastic state) at the time of working. When soil is in a friable state it is in the optimum state for cultivation. Nevertheless, soil compaction through compression can still occur especially as soil moisture approaches the lower plastic limit, as coarser pores (i.e. greater than 0.05 mm) are still mainly air-filled and able to reduce in volume (Spoor, 1975). Thus, soils at field capacity (start of drainage) are especially prone to compaction.
- Clay and medium soils tend to be at greatest risk of structural damage due to the longer periods of time during which the soil is in the plastic state following prolonged or heavy rainfall. Heavy soils also have lower bearing strength when wet and are therefore more susceptible to compaction during trafficking, grazing and cultivation than soils with a lower clay content (Holman *et al*., 2003).
- Soils also differ in terms of the proximity of field capacity to the lower plastic limit. For example, some clay and medium soils that are above their lower plastic limit at field capacity need several

days without rainfall before they can be cultivated (Davies *et al*., 1972). By contrast, many sandy soils are not plastic and do not have a lower plastic limit. Recently cultivated soils that are mechanically weak are also more liable to damage than a well-structured soil in stubbles or under grassland.

- The soil water content corresponding to the Atterberg lower plastic limit has been used as a threshold for soil workability (Thomasson, 1982). The Atterberg consistency limits describe the moisture-dependent soil strength behaviour in a relatively simple manner (Müller *et al*., 2011). It is based on the upper plastic limit (UPL) and the lower plastic limit (LPL) of soil. The consistency index *Ic* is a measure of relative soil strength

  $Ic = (UPL – w) (UPL – LPL)^{-1}$

  where w is the actual soil water content, *Ic* is dimensionless, UPL, LPL and w are given in kilogram water per kilogram dry soil. Müller *et al*. (2011) report that a consistency index of *Ic* = 0.75 is an acknowledged arbitrary limit of workability, albeit that there is a range of values in the literature from 0.7-0.9.

- Figure 28 shows a consistency diagram for some soils of different texture. The arbitrary workability limit (*Ic* = 0.75) ranges from about 16 to 50% gravimetric water content (0.16 kg/kg to 0.50 kg/kg) over the range of soils indicated in Figure 28. A guide to the field assessment of consistency states and indices is given in Table 50.

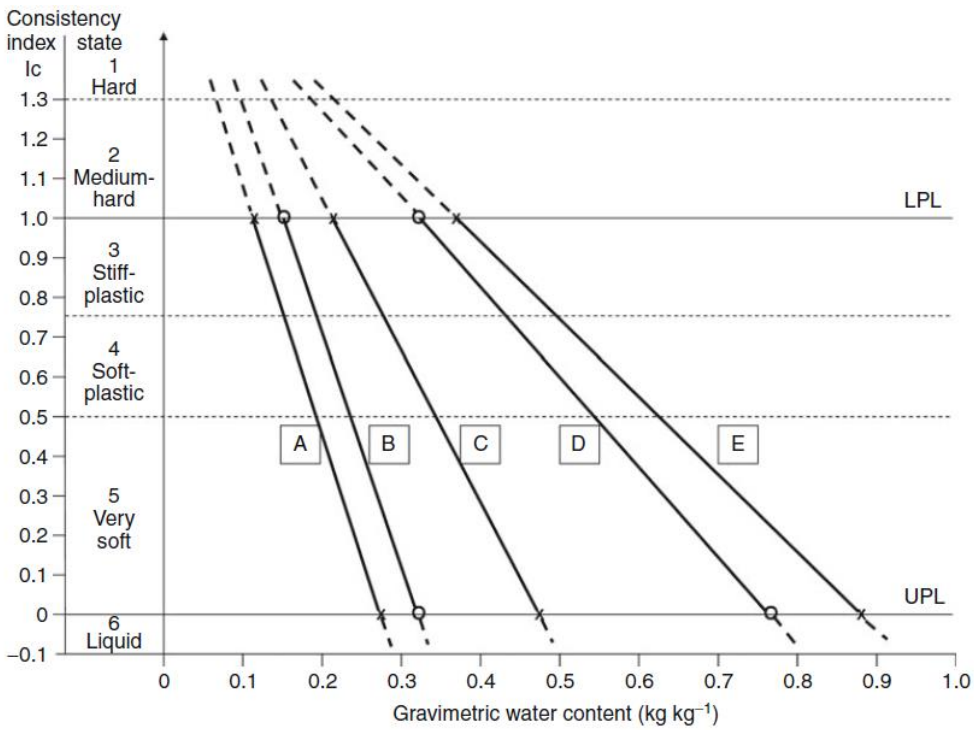


Figure 28. Consistency based on lower plastic limit (LPL) and upper plastic limit (UPL). A-E represent ranges for five typical topsoils in Germany with 15, 20, 30, 40 and 50% clay contents, respectively (Source: Müller *et al*., 2011).

Table 50. Field assessment of consistency states (Source: Müller *et al*., 2011).

No.	Consistency state	*Ic*	Field conditions
1	Hard	>1.3	Very dry, light, hard, brittle, no clods formable
2	Medium hard	1-1.3	Dry, not rollable to 3 mm diameter thread, fissuring, and crumbling, weakly stable clod can be formed
3	Stiff plastic	0.75-1	Moist, rollable into 3 mm diameter thread without crumbling, non-sticky
4	Soft plastic	0.5-0.75	Wet, easily deformable, rollable into 3 mm diameter thread without crumbling, sticky
5	Very soft	0-0.5	Very wet and sticky, not rollable
6	Liquid	<0	Extremely wet, muddy, sliding out of the hand

- Petelkau, 1984 (cited by Müller *et al*., 2011) suggested ranges of moisture contents that equated to workability. He used the water content at a suction of 5 kPa (i.e. 0.05 bar) as a reference basis. Figure 29 shows that sandy soils (upper part of the graph) are workable at most water contents. In comparison, soils with a higher proportion of fine particles (lower part of the graph), are workable over a smaller range of water contents.

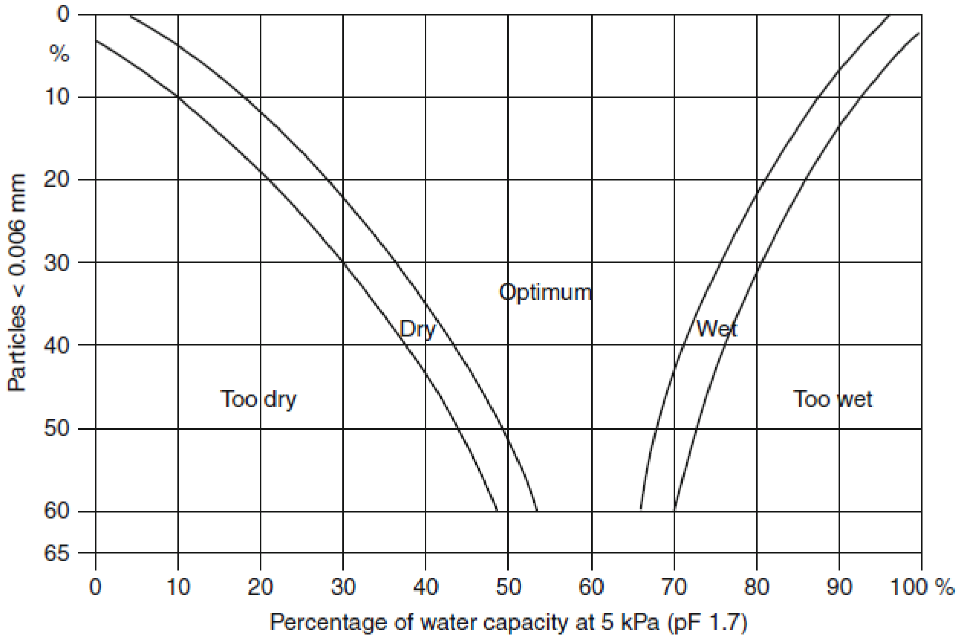


Figure 29. Ranges of water content for tillage (Source: Müller *et al*., 2011, adapted from Petelkau, 1984).

- Dexter and Bird (2001) developed equations for predicting the optimum water content for tillage as well as the upper (wet) and lower (dry) limits. Figure 30 shows the relations of the limits to soil clay content indicating that the range of water contents for tillage decreases with increasing soil clay content. For example, when the clay content is *c*.5% (0.05 kg/kg), the range of workable water contents ranges from *c*.13 to *c*.21% (0.13 to 0.21 kg/kg), whereas when the clay content is 60% (0.6 kg/kg) the workable water content only ranges from c.20-24% (*c*.0.20 to *c*.0.24 kg/kg).

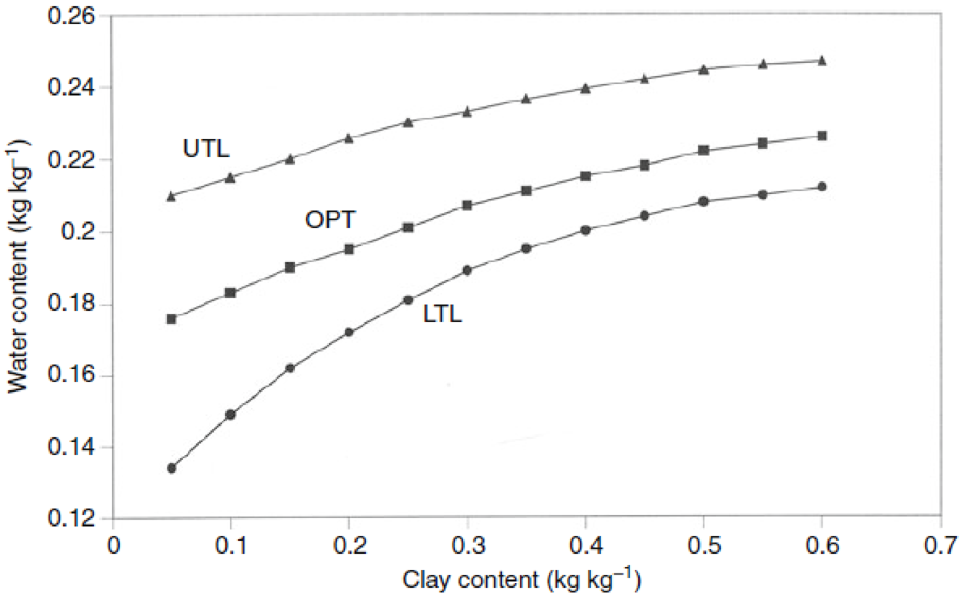


Figure 30. Values of the upper tillage limit UTL, the optimum tillage moisture content OPT (inflection point), and the lower tillage limit LTL as functions of soil clay content (After Dexter and Bird, 2001).

14.4 Decision support tools

- Müller and Schindler (1999) devised a matrix based on soil water content and expert opinion for predicting field trafficability, which was validated with more than 60 soils at different moisture conditions, Table 51. For example, where the density status is medium, the surface layer dry with a consistency state of 1 (water content <0.15 kg/kg), layer 2 has a consistency state of 2 (water content 0.15-0.22 kg/kg) and layer 3 has a consistency state of 3 (water content 0.22-0.28) the resulting trafficability score is 1 (practical). A score of 1.5 is the limit for trafficability.

- Edwards *et al*. (2016) combined methods for evaluating workability and trafficability to produce a decision support tool for assessing the readiness of a location for tillage operations over time. Three soils within a field were examined using the proposed tool to estimate the number of days they were suitable for conventional tillage and minimum tillage over an 11-year period. The soils were assessed for trafficability, workability and when they were both trafficable and workable (referred to as 'readiness'). The assessments were based on the soil texture, simulated soil water content and physical parameters of machines likely to be used for the defined operations. Workability and trafficability were estimated using mathematical models.

- Figure 31 shows an example of the workability limits with the soil water content plotted at four depths. The workability limit is shown as dashed lines; the soil is workable when the simulated water content at all depths is within the workability limits, i.e. mid to late September.

Table 51. Trafficability as a result of consistency and density of soils for a wheeled tractor with medium tractive force requirements (Source: Müller and Schindler, 1999).

Consistency at depth 0–2 cm	Consistency at depth 2–10 cm	Consistency at depth 10–30 cm																	
		Soil density low						Soil density medium						Soil density high					
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	1	1	1	1	1	2	3.5	1	1	1	1	2	3.5	1	1	1	1	2	3.5
Hard	2	1	1	1	2	3	4	1	1	1	2	3	4	1	1	1	1.5	3	4
$Ic > 1.3$	3	1	1	1.5	2.5	3.5	4	1	1	1.5	2	3	4	1	1	1	2	3	4
	4	1.5	1.5	2	3	4	4	1.5	1.5	1.5	2.5	3.5	4	1.5	1.5	1.5	2.5	3.5	4
	5	2.5	2.5	3	3.5	4	4	2.5	2.5	3	3	3.5	4	2.5	2.5	3	3	3.5	4
	6	3	3	3.5	4	4	4	3	3	3.5	4	4	4	3	3	3.5	4	4	4
2	1	1	1	1	1.5	2	4	1	1	1	1	2	4	1	1	1	1	2	4
Medium-hard	2	1	1	1.5	2	3	4	1	1	1	2	2.5	4	1	1	1	2	2.5	4
$Ic = 1–1.3$	3	1	1	1.5	2.5	3.5	4	1	1	1.5	2	3.5	4	1	1	1	2	3	4
	4	2	2	2.5	3.5	4	4	2	2	2	2.5	3.5	4	2	2	2	2.5	3.5	4
	5	2.5	2.5	3	3.5	4	4	2.5	2.5	3	3.5	4	4	2.5	2.5	3	3.5	4	4
	6	3	3	3.5	4	4	4	3	3	3.5	4	4	4	3	3	3.5	4	4	4
3	1	1	1	1	2	3	4	1	1	1	2	3	4	1	1	1	2	3	4
Stiff-plastic	2	1	1	1.5	2.5	3.5	4	1	1	1	2	3.5	4	1	1	1	2	3.5	4
$Ic = 0.75–1$	3	1	1.5	2.5	3	4	4	1	1	2	3	4	4	1	1	2	2.5	4	4
	4	2	2	3.5	4	4	4	2	2	3	3.5	4	4	2	2	2.5	2.5	4	4
	5	2.5	3	3.5	4	4	4	2.5	3	3	3.5	4	4	2.5	3	3	3.5	4	4
	6	3	3	4	4	4	4	3	3	3.5	4	4	4	3	3	3.5	4	4	4
4	1	1.5	1.5	2	3	3	4	1.5	1.5	2	3	3	4	2	2	2	3	3	4
Soft-plastic	2	1.5	2.5	2.5	3	3.5	4	1.5	2	2.5	3	3.5	4	2.5	2.5	2.5	3	3.5	4
$Ic = 0.5–0.75$	3	2	2.5	3.5	4	4	4	2	2	3	4	4	4	2.5	2.5	3	4	4	4
	4	2.5	3	4	4	4	4	2.5	2.5	3.5	4	4	4	3	3	3	4	4	4
	5	3	3	4	4	4	4	3	3	3	4	4	4	3	3	3	4	4	4
	6	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
5	1	2.5	3	3	4	4	4	2.5	3	3	4	4	4	3	3	3	4	4	4
Very soft-	2	3	3	3.5	4	4	4	3	3	3.5	4	4	4	3	3	3.5	4	4	4
$Ic = 0–0.5$	3	3	3	4	4	4	4	3	3	4	4	4	4	3	3	4	4	4	4
	4	3	3.5	4	4	4	4	3	3.5	4	4	4	4	3	3.5	4	4	4	4
	5	3.5	3.5	4	4	4	4	3.5	3.5	4	4	4	4	3.5	3.5	4	4	4	4
	6	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
6	1	3	3	3.5	4	4	4	3	3	3.5	4	4	4	3.5	3.5	3.5	4	4	4
Liquid	2	3	3	4	4	4	4	3	3	4	4	4	4	3.5	3.5	4	4	4	4
$Ic < 0$	3	3.5	3.5	4	4	4	4	3.5	3.5	4	4	4	4	3.5	3.5	4	4	4	4
	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	6	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Notes. Consistency states for three soil layers. Low density: recently ploughed soil, medium density: consolidated soils and high density: no till soils. Trafficability, 1: practical, 2: limitedly practical, 3: poor practice, 4: not practical. A score of 1.5 is the threshold for trafficability.

- Figure 32 shows an example of the trafficability limit, it illustrates how the stress at a depth of 50 cm varies over the autumn period. There were two periods during the autumn when the soil was trafficable for conventional tillage (14 days in total). However, after mid-October the stress caused by the front tyre of the tractor exceeded the limit of 50 kPa for the remainder of autumn.

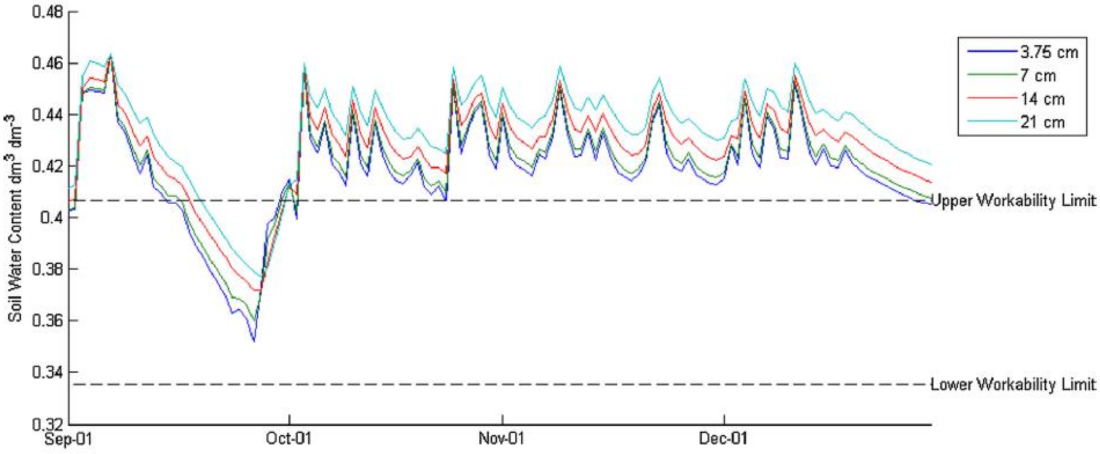


Figure 31. Example of workability limits based on soil water content. Only the days in late September when the soil water content is between the lower and upper limits are workable (Source: Edwards *et al*., 2016).

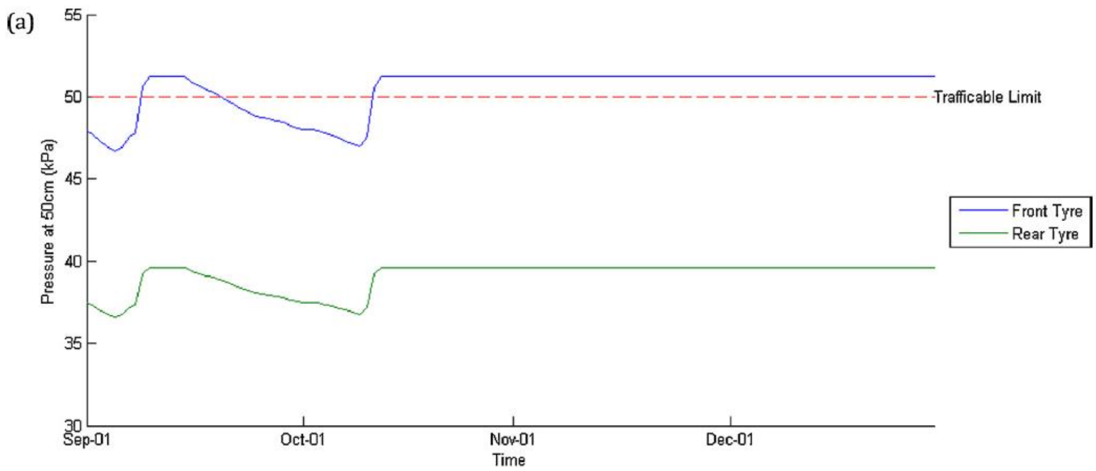


Figure 32. Stress at 50 cm below the soil surface. There are 14 days when the soil is trafficable when the pressure at 50 cm is <50 KPa (the blue line is below the red line). Source: Edwards *et al*., 2016.

- Figure 33 shows the workability, trafficability and readiness; in this example, the soil was workable for longer than it was trafficable. In this example, readiness depended on trafficability.

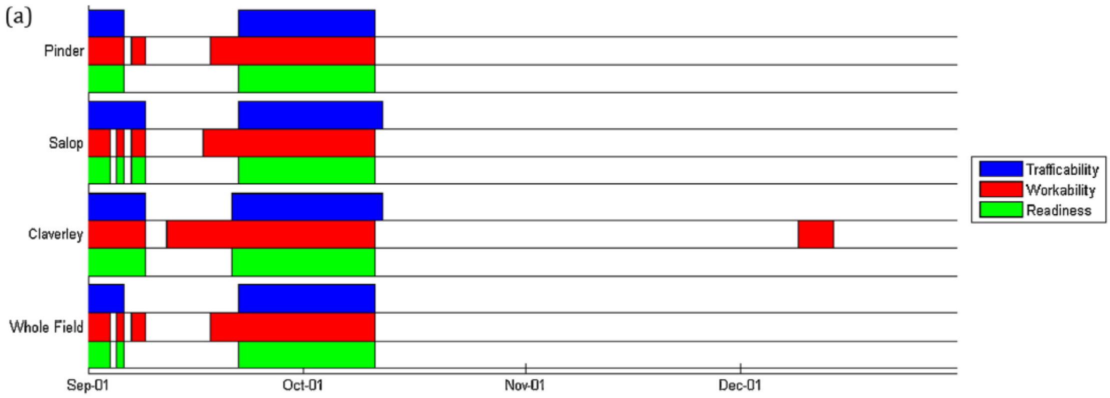


Figure 33. Example of trafficability, workability and readiness for three soils and the whole field (Source: Edwards *et al.*, 2016).

14.4.1 SOILAssist: Decision matrix for trafficability

- The German SOILAssist (sustainable securing and improvement of soil functions through intelligent land management[12]) project developed a decision matrix for trafficability based on soil texture, soil moisture (as a % of field capacity) and expert knowledge. It was designed to support on-farm decision making (Figure 34).

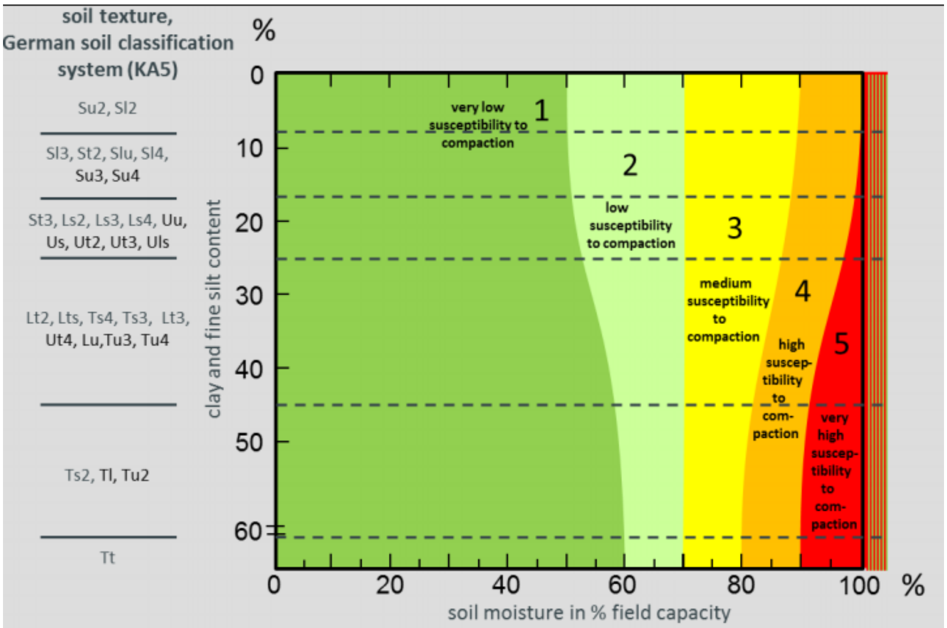


Figure 34. German SOILAssist trafficability matrix to identify the risk of soil compaction according to soil texture and soil moisture (% of field capacity).

[12] https://www.soilassist.de/

14.5 Mapping soil trafficability

- Chipanshi *et al*. (2018) determined the frequency of days with poor soil trafficability across the Canadian Prairies from simulated soil moisture at soil polygon level during the growing season (April to September) with the Versatile Soil Moisture Budget (VSMB) model (Baier *et al*., 2000). The assessment of soil trafficability was limited to those polygons with good suitability rating (according to the LSRS) for growing grain crops.
- Each soil polygon had a pre-determined critical soil moisture threshold in the first layer (0–5 cm) to trigger poor trafficability. Poor trafficability thresholds were set at ≥80% of field capacity for clay soils (> 40% clay content) and ≥90% of field capacity for all other textures. In comparison, early work in Canada on trafficability/workdays used the critical soil moisture level of less than 97.5% of field capacity for heavy machinery and deep cultivation and greater than 90% of field capacity for lighter equipment and shallow cultivation (Baier, 1973).
- Soil trafficability was summarised at monthly time scales from April to September at the 25th, 50th and 75th percentile levels (see example map in Figure 35). Data was further categorised into start, middle and end of the growing season (i.e. May, July and September). The authors found that poor soil trafficability was mainly associated with fine textured clay soils. On average, soils with higher clay content had 5 to 9 days of poor trafficability at seeding time (May). The wet phase represented by the 75th percentile category showed that 10–14 days of poor trafficability can be expected on soil polygons with heavy textures; there were fewer days (1–4) with poor trafficability during dry years (the 25th percentile binned values).

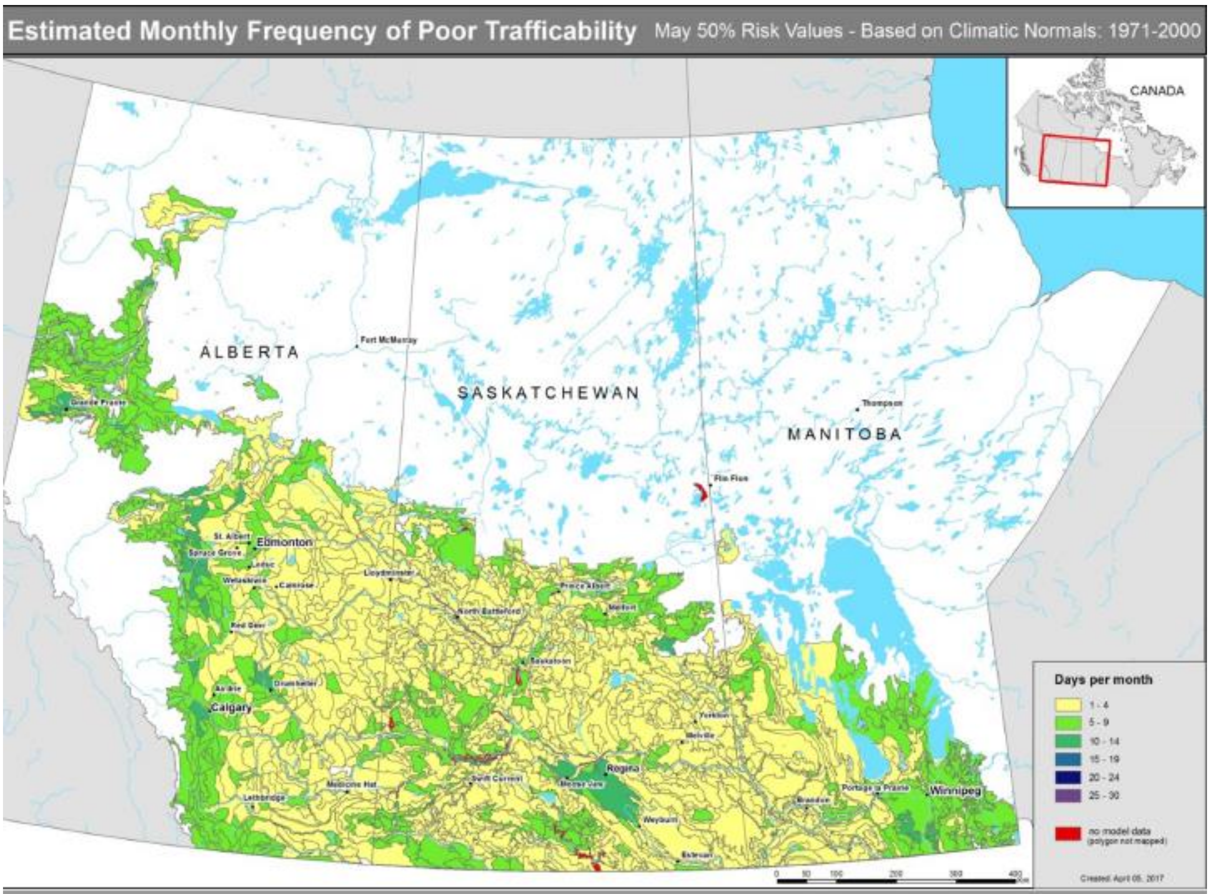


Figure 35. Estimated monthly frequency of poor trafficability at the 50th percentile level for May (Source: Chipanshi *et al*., 2018).

14.6 Satellite assessment of trafficability

- Carranza *et al*. (2019) suggested that Sentinel-1 satellites, which carry a SAR (synthetic aperture radar)[13] instrument, are promising sources of soil moisture information that would be suitable for mapping and monitoring field trafficability at field scale. However, measurements are only sensitive to around 5 cm soil depth. Measurements to assess trafficability require measurements over the top 20-30 cm, which would require the extrapolation of surface soil moisture data to be useful for trafficability assessments.
- Carranza *et al.* (2019) collected data from soil moisture sensors installed at 5, 10, 20, 40 and 80 cm below ground, in situ surface soil moisture and cone penetrometer readings from study fields in the Netherlands. The authors utilized the 5 cm soil moisture measurements as reference values to validate the soil moisture data from Sentinel.
- As the first step to relate satellite-derived surface soil moisture to field trafficability, Carranza *et al.* (2019) investigated when surface soil moisture was a good indicator of subsurface soil moisture conditions. The 5 cm field values represented surface soil moisture and the 20 cm field values represented subsoil moisture at the depth which would carry the weight of the machinery. The results showed coupled conditions for soil moisture at $\geq 19\ cm^3/cm^3$ where there was almost a 1:1 correspondence between surface and subsurface values. As a result, the authors suggested that Sentinel-1 satellite data could be used for the assessment of trafficability.

14.7 Conclusions

- Soil workability and trafficability are implicit in the ALC rather than explicit. They are based on the interrelated factors of field capacity days, soil texture and characteristics (gleying and permeability) and the duration of waterlogging. ALC grade according to wetness is highest where FCD are low, soil texture is light (e.g. sandy loam), and the duration of waterlogging is short. Similar conditions are likely to characterise sites that are workable and trafficable over long periods.
- Several authors have established methods for assessing workability and trafficability. Most are designed to facilitate practical decision making by farmers, e.g. identifying conditions suitable for cultivation. In contrast, the original aim of the ALC was to support planning policy and protect the long-term capability of the best and most versatile land (ALC Grades 1-3a).

[13] Techniques using microwave remote sensing are divided into active and passive methods. Passive microwave remote sensing measures the intensity of microwave emissions from the Earth's surface, expressed in terms of brightness temperatures. Active microwave remote sensors supply their own source of illumination. They transmit signals towards a target and measures the portion scattered back. Synthetic aperture radar (SAR) is an active microwave sensing technique providing observations with a high spatial resolution

15 Summary

15.1 ALC climate data suitability

- The current ALC climatic dataset (although dated) provides a single data source, which facilitates comparison between sites (i.e. all sites that are ALC Grade 1 have the same degree of limitation, e.g. for Grade 1, no or very minor limitations due to climate). Prior to the publication of the 1988 ALC guidelines, maps or meteorological station data would have been used to estimate climatic parameters at a site. However, both the manual interpretation of maps and the extrapolation of data (without specific guidance) relied on subjective judgements and so were less accurate than the current use of the single reference dataset.
- Both ADAS (2004) and Keay *et al*. (2014) identified differences in temperature and summer rainfall, compared to the current ALC dataset. It is likely that the return to FC will be changed by lower ASR, which suggests that calculations based on the original ALC climate dataset may not be accurate. Keay *et al*. (2014) suggested that although the overall duration of field capacity might not change much in the future, it will start later (in autumn) and end later (in spring). In contrast, Arnell and Freeman (2021) (using climate data for 1981-2010 and UKCP18 projections) reported that the number of days with soils at field capacity decreased through the twenty-first century, primarily due to soils being drier for later into autumn (Rivington *et al*. 2013). This was despite the projected general increase in autumn rainfall and occurred because greater evaporation meant soil moisture deficits persisted for longer into autumn.
- The ALC system should be reviewed using contemporary weather and crop yield statistics to determine the significance of the wetness factor for the grading of agricultural land in England and Wales.

15.2 ALC wetness assessment

- The ALC method wetness method is based on the results of MAFF and SSLRC soil water regime monitoring projects carried out between 1964 and 1985 (323 site years from 184 sites).
- The ALC wetness assessment considers two main factors:
    - o wetness of the cultivation zone or upper soil layers in grassland and
    - o wetness in the full rooting zone/whole soil profile
- The wetness of the cultivation zone is influenced by the amount of water retained and the wetness of the climate. Soil texture is a major influence on the amount of water retained and for a given soil texture the wetter the climate the greater the poaching risk and potential workability challenges. However, although soil texture and climatic wetness are important characteristics affecting poaching and workability, waterlogging occurring below the cultivation zone is also important. Even if the subsoil waterlogging does not reach up into the cultivation zone the wetness of the zone may be increased by upward movement of water by capillary action (Jones *et al*., 1992). The effect of subsoil waterlogging depends on both the depth at which it occurs and the duration of that occurrence.

15.2.1 Wetness in the cultivation zone

- As noted above the wetness of the cultivation zone is strongly influenced by, i) the amount of water retained and ii) the wetness of the climate. These two factors are considered in the ALC wetness assessment through consideration of soil texture in the top 25 cm of the profile and field capacity days (as a proxy for climate).

- Soil texture (of the top 25 cm) is used as part of the process for allocating the ALC grade according to soil wetness (1-5). The ALC includes five soil texture groups which have been defined according to water retention, workability characteristics and susceptibility to damage by grazing animals; for a given climate Group 1 is the most workable and Group 5 the least. The soil groupings are used in ALC as part of the procedure for allocating the final ALC grade according to soil wetness.
- FCD ranges are used as a proxy for climatic wetness zones; within each range similar soils are assumed to behave in a comparable manner in terms of workability or poaching risk. For a given soil texture the wetter the climate the greater the poaching risk and workability problems. The choice of FCD ranges was based on field experience from ADAS advisory work and knowledge gained from previous ALC surveys. The ranges are <126, 126-150, 151-175, 176-225 and >225.

15.2.2 Wetness in the rooting zone/whole soil profile

- Although the soil texture of the top 25 cm and climatic wetness are important factors affecting workability and poaching risk these limitations are also affected by waterlogging occurring below the cultivation zone. The severity of the effect of subsoil waterlogging depends on i) the depth at which it occurs and ii) the duration of waterlogging. Generally, the shallower and more prolonged the waterlogging the more severe the limitation. The criteria above are the basis of the six soil wetness classes (I-VI). Depth is defined by reference to three depth zones, i.e. <40 cm, 40-70 cm and >70 cm and duration is measured in days per annum.
- The key soil profile characteristics used to assess wetness class in soils with slow permeability are depth to gleyed horizon and depth to slowly permeable layer and climate (field capacity days). For permeable groundwater gley soils, depth to gleyed layer, subsoil texture and climate (field capacity days are used to determine soil wetness class. Waterlogging is generally of shorter duration if the subsoil is coarse textured and therefore very permeable. For this reason, the methodology for assessing wetness class in soils which lack an SPL requires a distinction to be made between those with and those without coarse textured subsoils.

15.2.3 Final ALC grade

- Once the wetness class (I-VI), texture of the top 25 cm of soil and field capacity days have been determined the ALC grade (1-5) can be allocated. Broadly, as the soil texture group indicates reduced workability and increased susceptibility to grazing damage the ALC grade is lower (in quality terms), so that for the same wetness class and FCD soils in the first group (i.e. for mineral soils, S, LS, SL and SZL) will have a higher ALC grade than those in the last group (SC, ZC and C).
- The effect of wetness class on ALC grade can be seen in the following Tables which are extracted from ALC Table 6. In the first example a soil with a silt loam texture (a good agricultural soil) shows a general trend to move towards a lower ALC grade (in quality terms) as soil wetness class increases (e.g. wetness class I/FCD <126 = ALC Grade 1 and wetness class V/FCD <126 = ALC Grade 5), Table 52. However, as climatic wetness increases from <126 FCD to >225 FCD there is not always a change in ALC grade (e.g. wetness class III/FCD <126 = ALC Grade 3a; wetness class III/FCD 176-225 = ALC Grade 3a). Also, in wetter areas, moving to a worse wetness class does not always reduce ALC grade (e.g. >225 FCD/wetness class II = ALC Grade 3a; >225 FCD/wetness class IV = ALC Grade 3a). And for wetness classes IV, I and VI the ALC grade varies little over all climatic zones; subsoil waterlogging is the most limiting.
- A second example for clay shows generally lower grades (in quality terms) than for silt loan because clay has a greater wetness limitation (higher retained water and lower permeability),

Table 53. Generally, as wetness class increases ALC grade decreases (in quality terms), however, the same ALC grade may apply over several wetness classes. The final example shows the ALC grade allocated to organic clay soil, which illustrates the effect of higher organic matter content on grade, Table 54. For example, where FCD <126 and soil wetness class is I, clay soil is allocated ALC Grade 3a and organic clay soil ALC Grade 1. This is because in dry areas with good soil drainage the organic matter enhances workability. However, in drier areas with more waterlogged soils (e.g. FCD <126 and soil wetness class IV) the clay soil is ALC Grade 3b and the organic clay soil is ALC Grade 4. As wetness increases (either through increased FCD or worse soil wetness class) organic matter increases water retention and reduces soil bearing strength.

Table 52. ALC grade for silt loam soil in relation to soil wetness class and climatic wetness (Source: MAFF, 1988).

Silt loam	Wetness class	Increasing climatic wetness				
		Field capacity days				
		<126	126-150	151-175	176-225	>225
Increasing subsoil waterlogging	I	1	1	1	2	3a
	II	2	2	2	3a	3b
	III	3a	3a	3a	3a	3b
	IV	3b	3b	3b	3b	3b
	V	4	4	4	4	4
	VI	5	5	5	5	5

Table 53. ALC grade for clay soil in relation to soil wetness class and climatic wetness (Source: MAFF, 1988).

Clay	Wetness class	Increasing climatic wetness				
		Field capacity days				
		<126	126-150	151-175	176-225	>225
Increasing subsoil waterlogging	I	3a	3a	3a	3b	3b
	II	3a	3b	3b	3b	3b
	III	3b	3b	3b	4	4
	IV	3b	3b	3b	4	5
	V	4	4	4	5	5
	VI	5	5	5	5	5

Table 54. ALC grade for organic clay soil in relation to soil wetness class and climatic wetness (Source: MAFF, 1988).

Organic clay	Wetness class	Increasing climatic wetness			
		Field capacity days			
		<126	126-175	176-225	>225
Increasing subsoil waterlogging	I	1	2	3b	*
	II	2	3a	3b	*
	III	3a	3a	4	*
	IV	4	4	4	
	V	5	5	5	5
	VI	5	5	5	5

15.3 Assessment of soil wetness in other land classification systems

- Soil wetness is included as a component of many other land capability and suitability assessments. The methods for assessing soil wetness in other systems often have some similarities to the ALC. This is unsurprising given that the factors which drive soil wetness are likely to be similar. However, many systems are less detailed than the ALC. For example, the New Zealand Land Use Capability (LUC) system includes wetness as one of the four main physical limitations which are considered to limit land use capability. However, there are no specific limits or definitions for the wetness subclasses, and it is recognised that there will be regional variations. Also, the LUC does not explicitly consider climate or soil texture as part of the assessment of soil wetness. Similarly, the German Muencheberg Soil Quality Rating system acknowledges the importance of soil wetness particularly in terms of the influence on plant growth although the assessment of soil wetness is limited and qualitative. Reference is made to the effect of numerous days with topsoil water content higher than the plastic limit on soil management (referred to as technological wetness). The Scottish system (Land Capability Classification for Agriculture-LCA) is the most like the ALC (both have similar backgrounds) taking account of soil texture, climate (field capacity days) and soil wetness classes. In addition, the LCA also includes an explicit assessment of soil workability.

15.4 Trafficability and workability assessments

- Modern agriculture relies on machinery to carry out farming operations such as tillage and harvesting. Soil wetness influences the sensitivity of the soil to structural damage and is therefore a major factor in determining the number of days when the soil is in a suitable condition for cultivation (workability), trafficking by machinery or grazing by livestock. Currently the ALC does not directly assess either workability or trafficability but instead considers some of the factors that influence it, i.e. soil wetness and texture.
- Soil workability and trafficability are implicit in the ALC rather than explicit. They are based on the interrelated factors of field capacity days, soil texture and characteristics (gleying and permeability) and the duration of waterlogging. ALC grade according to wetness is highest where FCD are low, soil texture is light (e.g. sandy loam), and the duration of waterlogging is short. Similar conditions are likely to characterise sites that are workable and trafficable over long periods.
- Several authors have established methods for assessing workability and trafficability. Most are designed to facilitate practical decision making by farmers, e.g. identifying conditions suitable for cultivation. In contrast, the original aim of the ALC was to support planning policy and protect the best and most versatile land (ALC Grades 1-3a).

16 Strengths and weakness of ALC wetness/workability assessment

- Soil wetness and workability is influenced by several factors. These factors include soil properties (e.g., texture, structure or organic matter content); climate (e.g., rainfall, evapotranspiration) and topography (e.g. slope or soil depth). However, as the ALC method is intended for large-scale strategic assessment of wetness and workability the local role of topography in influencing drainage rates is not considered (although it is part of the wider ALC assessment). For wetness risk, the potential for soil structural damage is evaluated using 1) intrinsic soil vulnerability properties (that determine the strength and plasticity of the topsoil together with soil profile variations that control drainage) and 2) the frequency and duration of wet conditions in the climate regime.
- The underlying assumptions of the ALC system for the assessment of soil wetness and workability remain sound and it provides a comprehensive assessment of the main factors that affect soil wetness on a broad scale. No major changes to the methodology have been proposed although a number of recommendations have been made to update and improve the guidance (see Section 17. Recommendations for more details). Most of these are designed to make explicit some of the assumed knowledge in ALC (e.g. how to use a Munsell soil colour chart) and to clarify terminology (e.g. soil structure types, soil consistence, soil mottling etc.). Similarly, it is recommended that future iterations of the ALC should consider making the assessment of workability and trafficability more explicit.
- The only major recommendation for the ALC soil wetness assessment is to update the underlying field capacity dataset. The number of days at field capacity is an important part of the soil wetness assessment, however, the ALC data on the duration of field capacity is more than 50 years old. As this forms an integral part of the wetness assessment and with increasing evidence of changing climate it is recommended that this dataset is updated.
- The strengths and limitations of the methodology are outlined in Table 55, below.

Table 55. Strengths and limitations of ALC wetness/workability assessment

Strengths	Description
Well recognised	Developers and local planning authorities use ALC to inform decisions on the appropriate sustainable development of land. It is used to identify the best and most versatile land (i.e. ALC Grades 1, 2 and 3a). The current method of assessment has been in use since 1988, with earlier versions dating back to 1966.
Comprehensive	The assessment of soil wetness includes consideration of the climate, soil texture and the soil water regime. The soil water regime identifies the soil wetness class through pedotransfer functions (based on acknowledged relationships between soil features (gleying, structure, permeability etc.) and can be determined using easily available data.
Cost effective	The assessment of soil wetness through dipwells or borehole monitoring is very expensive. Using the ALC pedotransfer function is much more cost effective.
Wide ranging	The assessment of soil wetness is very detailed and accounts for a wide range of possible soil type/texture/climate combinations.

Strengths	Description
	Special consideration is given to red soils (which do not exhibit gleying despite having impeded drainage) and to calcareous soils (which have better structure and workability than non-calcareous soils when the climate is not too wet). .
Based on sound science	Soil wetness is based on 1) intrinsic properties that determine the strength and plasticity of the topsoil together with soil profile variations that control drainage (i.e. a slowly permeable layer) and 2) the frequency of wet conditions in the climate regime. The underpinning science and data is comprehensive and very sound. It has essentially not been superseded in most areas.
Fixed reference point	Land that is graded, for example ALC Grade 1 or soil wetness class III, in any part of England and Wales have similar biophysical characteristics providing a fixed reference point. The system also allows for detailed site level assessments.
Limitations	
Complicated	The system is complicated. The assessment of soil wetness has many parts and relies on expert knowledge to correctly identify the soil wetness class.
Assumed knowledge	The wetness assessment requires significant assumed knowledge. This is not unexpected as the system is designed to be used by professional soil scientists or ALC specialists and is not designed to be used without training. Despite this, it is suggested that the system could be made more transparent if some of the assumed knowledge was included within the ALC guidance (e.g. how to use Munsell Soil Colour charts or additional details on soil structure).
Limited number of skilled practitioners	Proficiency in the conduct of an ALC survey requires knowledge and experience of field soil survey and the interpretation of soil, topography and climate data. There are comparatively few experts capable of carrying out ALC to a sufficient professional standard. There is no register of ALC surveyors or recognised qualification.
Reliance on old data	The climatic datasets used in ALC are dated and therefore may not reflect current climatic conditions. In addition, some of the equations used to define climate parameters may be outdated. For example, it is suggested that the equation which predicts FCD could be based on average summer and winter rainfall rather than annual rainfall.
Reliance on averages and medians	Climate change predictions suggest that the weather is likely to become more extreme in the future. This suggests that it will be more important to consider not just the average climatic conditions but also the variation around that average. For example, the probability of exceeding a certain number of FCD might be important as well as the mean/median value.

17 Recommendations

- In simple terms the assessment of soil wetness in the ALC is based on determining how much water the soil receives and what happens to that water. Soil permeability is related both to soil texture and soil structure. Pore size and number (which are closely related to soil texture and structure) control the rate of infiltration and percolation. Finer soil textured soils (e.g. clay) are much less permeable than coarse (sandy) textured soils. Soil structural condition will modify the rate of permeability with compacted soils much less permeable than well-structured soils.

17.1 Climate dataset

- *It is recommended that the reference climatic dataset used for the ALC should be reviewed*. The current ALC climate dataset is based on data from 1941-1970 (rainfall) or 1961-1980 (temperature) suggesting that it is potentially unrepresentative of current climatic conditions. Analysis of climate data indicates that most of the warmest years in Wales have occurred since 1990 (i.e. outside of the period covered by the ALC climate data). Keay *et al.* (2014) also noted changes in the AT0 and AAR (the two parameters used to allocate ALC grade according to climate), which also support the need to update the climate dataset.

- Climate change predictions suggest that the weather is likely to become more extreme in the future. This suggests that it will be more important to consider the variation around average values for climate parameters. *Further work is required to investigate how best to incorporate the influence of the probability of extreme events into the ALC methodology (e.g. frequency and severity of extreme events and to establish the methodology that would best capture the impact of weather extremes on agricultural land.* Such updates could include the addition of new parameters (e.g., longest dry spell) or revision to current criteria (e.g. the use of percentiles rather than absolute values).

17.2 Field capacity days

- In the ALC soil wetness assessment, the field capacity period is a meteorological parameter which estimates the duration of the period when the soil moisture deficit is zero with values derived from a mathematical model. Field Capacity Days (FCD) assessment integrates climate and soil characteristics in a dynamic manner since it accounts for spatial-temporal meteorological variability (Jones *et al.,* 2014).

- FCD is a more robust indicator of climatic wetness than average annual rainfall (AAR) as it reflects the duration of wetness, which is of relevance for field operations and incorporates evapotranspiration. In the ALC, FCD ranges are used as a proxy for climatic wetness zones. Within each FCD range similar soils are assumed to behave in a comparable manner in terms of workability or poaching risk. For a given soil texture the longer the duration of FC (i.e. the wetter the climate) the greater the poaching risk and restrictions on workability. The choice of FCD ranges was based on field experience from ADAS advisory work and knowledge gained from previous ALC surveys (Jones *et al*., 1992). ALC grade decreases as the texture of the top 25cm of soil becomes finer (i.e. increasing clay content) and as FCD increases.

- *It is proposed that the ALC data on the duration of FC is updated as it is currently based on 1941-1970 climate data*. The published MORECS dataset would be an appropriate dataset to use as it calculates SMD and would enable the identification of the start and end of field capacity based on, for example, the number of days when SMD = 0 mm. The MORECS dataset uses data from synoptic weather stations which is then interpolated to a 40 x 40 km gird (approximately 200 grid squares cover the UK). The dataset is available on a daily, weekly or monthly timescale. *The relationship between SMD and other climate or location variables could be used to update the regression equation for predicting FCD. It is likely that the 'best' regression for predicting FCD will include both summer and winter rainfall, rather than simply annual rainfall which forms the basis of the current equation*. Analysis of climate data suggests that annual rainfall has not changed significantly over time whereas changes to seasonal rainfall patterns have been noted potentially resulting in delays to both the end of FC and return to FC.

- Although the concept of field capacity has been criticised due to local variations and difficulties in demonstrating when equilibrium conditions are reached (Cavazza *et al.,* 2007), it has strategic value in providing a consistent relative measure of saturated conditions in a spatial and temporal context for land evaluation (Brown, 2017). As such, once the reference dataset has been updated it will continue to be a valuable metric in the assessment of soil wetness.

17.3 Gleyed horizon and soil colour

- Changes in soil colour (and the depth at which they occur) are the basis of the identification of a gleyed horizon in the ALC. Gley features develop in response to current soil conditions (namely waterlogging). However, in some cases the features may remain even though the waterlogged anaerobic conditions that created them no longer persist. Thus, some gley features may have formed under anaerobic conditions that no longer exist. *Updates to ALC guidance should include information on the identification of historical gley features.*
- In addition to gleying, soil mottling can develop if a soil is waterlogged for extended periods of time. Gleying implies uniform coloration while mottling indicates spots or patches with different (often highly contrasting) coloration. Mottling occurs when the soil becomes partially aerated between episodes of waterlogging. *To complement the guidelines for the identification of a gleyed horizon it is suggested that any future updates to the ALC include additional text to define "mottles" and some accompanying illustrations. Also, further guidance on the identification of the frequency of mottles noting that the important distinction for ALC purposes is to identify if there are >2% mottles (for example,* Figure 36*, below). Further investigation may be required to determine if 2% is a suitable threshold to indicate episodic waterlogging.*
- The identification of a gleyed horizon is based on Table 19, above, along with ALC Figure 4 which illustrates the Munsell soil colours referred to in the Table. *It is recommended that the ALC includes additional guidance on how to use a Munsell colour chart (i.e. comparing a freshly extracted moist soil sample with standard Munsell soil colour charts in good natural light). It is also recommended that ALC Figure 4 is redrawn or replaced to improve clarity.*
- The Munsell method for assessing soils is at best semi quantitative, because it is limited by a subjective match and by the number of Munsell colour chips (Baumgardner *et al*. 1985). Moritsuka *et al.* (2019) noted that overall, instrumental measurement (colorimeters) was much more repeatable than visual observation, although they concluded that further investigations were needed to evaluate whether the low-cost colorimeters could be effective across various environments including field conditions. It should be noted that in the ALC, colour is used primarily to (a) assess if a soil is brown or red and (b) to allocate a hue value chroma combination into a brown, pale, grey or ochreous category. Consequently, attribution to red, brown, pale, grey or ochreous is critical but the specific colour combination of hue, value and chroma within red, brown, pale, grey or ochreous groupings is much less important. *Alternative methods for describing/measuring soil colour should be considered in future iterations of the ALC.*

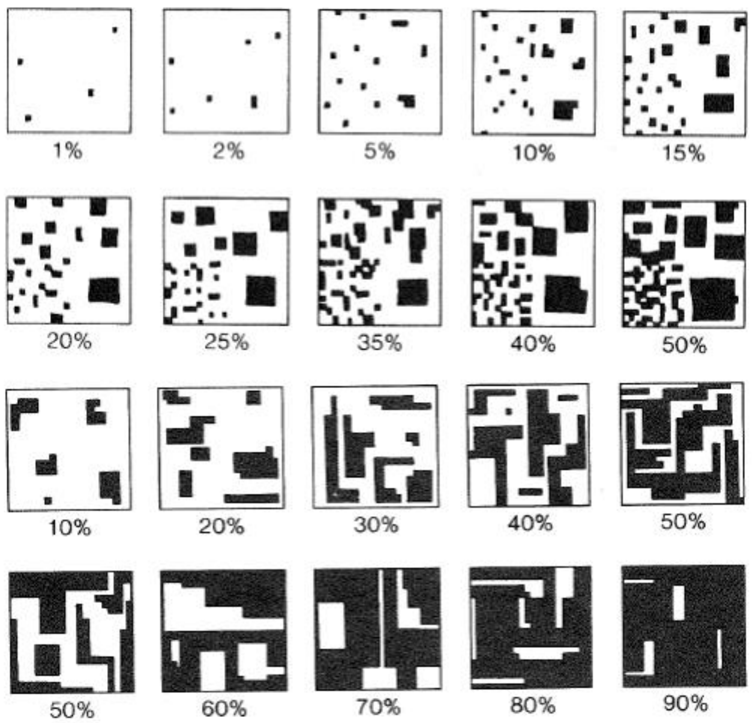


Figure 36. Soil mottles as % of soil area.

17.4 Slightly gleyed layer

- ADAS (1991) suggested that the depth to the top of the uppermost slightly gleyed layer could be used to determine the wetness class if the soil had no gleyed horizon. They listed four soil series which met the slightly gleyed criteria (Bishampton, Romney, Salwick and Rufford) although they noted that there may be others that met the requirement. Five other soil series are mentioned in the 1991 document (Kexby, Quorndon, Ollerton, Arrow and Blackwood) though it is not clear why these soils are included in the discussion. Given that there are relatively few soils of this type this suggests that the addition of this criteria would not have wide impact. ADAS (1991) suggested several amendments to the ALC text to incorporate the slightly gleyed horizon into the current ALC guidance. Importantly the amendments suggested by ADAS do not require additional Figures or Tables in the ALC guidance rather incorporation into existing ALC Figures 6/8 and Table 13. As such the changes would be simple to make. However, they would add another layer of complexity to an already complicated system. *It is suggested that further consideration should be given to whether to extend the wetness assessment to include the identification of a slightly gleyed horizon.*

17.5 Slowly permeable layer

- A slowly permeable layer has an important influence on the wetness limitation and provides a key measure of soil drainage characteristics. In physical terms, a slowly permeable layer has been defined by a saturated lateral hydraulic conductivity of <10 cm/day, but its presence may also be deduced from morphological criteria (texture and structure) in the soil profile. A slowly permeable horizon is recognized from the various combinations of these properties and its presence within the profile is confirmed by evidence of gleying in either that horizon or the one immediately above. However, soil structure types, biopores and soil consistence (used to describe a slowly permeable layer) are not defined in the ALC, although reference is made to the Soil Survey Field Handbook (Hodgson, 1976) for more details. *As a result it is suggested that any updates to the ALC guidance should include definitions of soil structure types, biopores and soil consistence. Also confirmation of what soil textures are included in the fine to very coarse categories in ALC Figure 5 (Figure 20, above).* Figure 37 is taken from the US Soil Survey Manual; a similar diagram could be included in the ALC guidance to describe soil structure types (or photos of soil structure types).

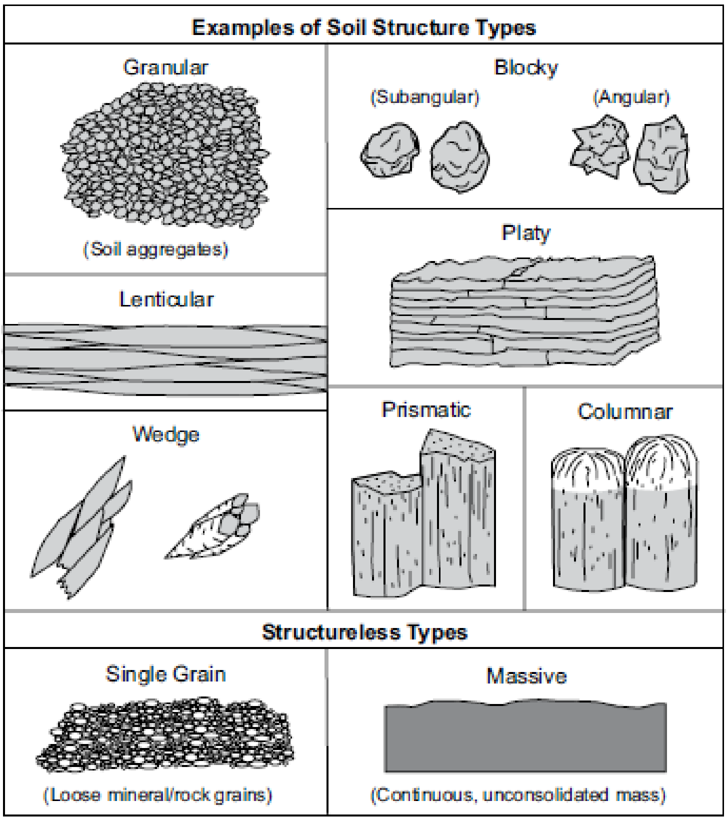


Figure 37. Example of soil structure (Source: USDA, 2017).

- Jones *et al.* (1992) describe biopores as continuous, connecting channels large enough to permit the movement of water under the effect of gravity. They note that porosity is assessed by breaking open a soil ped and comparing the abundance of pores >0.5 mm diameter with charts in the Soil Survey Field Handbook. This description should be included in ALC guidance.
- In addition, Jones *et al.* (1992) describe seven consistence categories ranging from loose to extremely firm and list both the force needed for failure in newtons and field methods for determining failure. Consistence describes the extent to which primary soil particles are packed and adhere together within soil structural units. Soils that have firm consistence (part of the criteria for describing SPL) crush or break when moderate force is applied by the thumb and forefinger. *An assessment of soil consistence forms part of the ALC pedotransfer function for the identification of an SPL but knowledge of soil consistence is assumed rather than described. As a result, it is suggested that a table of soil consistence categories is added to the ALC (Table 56, below).*

Table 56. Field assessment of soil consistence (Source: Jones *et al*., 1992).

Consistence category	Force needed for failure (newtons)	Field method and condition of failure
Loose	-	No specimen can be obtained
Very friable	<8	Specimen crushes or breaks when very slight force applied by thumb and forefinger
Friable	8-20	Specimen crushes or breaks when slight force applied by thumb and forefinger
Firm	21-40	Specimen crushes or breaks when moderate force applied by thumb and forefinger
Very firm	41-80	Specimen crushes or breaks when strong force applied by thumb and forefinger
Extremely firm	81-160	Specimen cannot be crushed or broken by thumb and forefinger but can be by squeezing slowly between hands
	>160	Specimen cannot be crushed or broken in hands but can be broken or crushed under foot by person weighing 80 kg applying weight slowly

- The current criteria for the identification of a slowly permeable layer (Table 23, above) is a pedologic definition that does not include rock or similar material with low permeability. However, many sedimentary rock types are somewhat porous and permeable (chalk, many sandstones etc) and some hard rocks are technically slowly permeable. In addition, rocks such as limestone may be fissured, and some igneous rocks have a 'columnar' blocky structure; both provide transport routes for excess soil water. *Future iterations of the ALC should consider whether the criteria used to identify a slowly permeable layer should also include reference to underlying lithology.*

17.6 Workability assessment

- Soil workability and trafficability are implicit in the ALC rather than explicit. They are based on the interrelated factors of field capacity days, soil texture and characteristics (gleying and permeability) and the duration of waterlogging. ALC grade according to wetness is highest where FCD are low, soil texture is light (e.g. sandy loam), and the duration of waterlogging is short. Similar conditions are likely to characterise sites that are workable and trafficable over long periods. In line with the Scottish LCA, *future iterations of the ALC should consider making the assessment of workability/trafficability more explicit. An additional Table (or Tables) could be included that identifies the combination of criteria that identify workable soils or soils at low risk of poaching.*

17.7 Computerised or online system

- *Consideration should be given to the automation of the soil wetness assessment e.g. by using a spreadsheet calculator*. This system would allow the user to input the parameters required to define the soil wetness class and subsequently the ALC grade for wetness. It would provide the opportunity to speed up the process and reduce the risk of errors (e.g. from using the 'wrong' ALC Figure or Table to assess the final ALC grade for wetness). In addition, it would standardise recording systems and potentially allow inputs to a centralised database and make the data more accessible for modelling subject to data protection. However, field assessment would still be required for data collection. Also, any automatic system would need caveats and warning when scores were near grade thresholds or near to soil wetness class boundaries to allow for expert opinion to override grading where necessary.

18 Review of ALC Tables and Figures used in soil wetness assessment

- As noted above the ALC uses several Tables and Figures to determine the ALC grade according to soil wetness. In chronological order these are:
    - ALC Table 6 (grade according to soil wetness – mineral soils),
    - ALC Table 7 (grade according to soil wetness – organic mineral and peaty soils),
    - ALC Table 11 (duration of soil wetness classes),
    - ALC Table 12 (estimation of wetness class of peat soils with no slowly permeable layer starting within 80 cm depth),
    - ALC Table 13 (Estimation of Wetness Class of mineral or organic mineral soils with no slowly permeable layer starting within 80 cm depth but with gleying present within 70 cm),
    - ALC Figure 2 (soil textural triangle, limiting percentages of sand, silt and clay fractions for mineral texture classes),
    - ALC Figure 3 (limiting percentages of organic matter, clay and sand for peaty and organic mineral texture classes).
    - ALC Figure 4 (diagrammatic representation of gley colours defined according to the Munsell soil colour system),
    - ALC Figure 5 (diagrammatic representation of the combination of structure, texture and consistence which are characteristic of slowly permeable layers,
    - ALC Figure 6 (flow diagram for assessing soil wetness class from field capacity days, depth to gleying and depth to slowly permeable layer,
    - ALC Figure 7 (estimation of wetness class from depth to slowly permeable layer and duration of field capacity for soils with gleying present within 40 cm depth and a slowly permeable layer starting within 80 cm depth and for peat soils with a slowly permeable layer and
    - ALC Figure 8 (estimation of wetness class from depth to slowly permeable layer and duration of field capacity for soils with gleying present within 70 cm depth but not within 40 cm and a slowly permeable layer starting within 80 cm depth.

- Some of the suggested changes to Tables and Figures have been discussed in earlier sections of these reports but all the recommendations are summarised in Table 57, below.

Table 57. Recommendations for updates or modifcations of ALC Tables and Figures for soil wetness assessment

Table or Figure	Short description	Updates or modifications required
ALC Table 6	Grade according to soil wetness (mineral soils)	Currently footnotes are used to indicate that sand “S” is not eligible for Grades 1, 2 or 3a and “LS” not eligible for Grade 1. However, these soil textures are grouped with others (SL and SZL) that can be graded as ALC 1-3a. For clarity, it is suggested that for wetness classes I-IV the first soil texture group should not include “S”. A separate row should be included for sand indicating the appropriate ALC grade for the wetness class/FCD combination. Alternatively, the footnote to ALC Table 6 should be modified to confirm that “S” soils will be graded as 3b for wetness classes I-IV. For wetness classes I and II, “LS” cannot be ALC Grade 1. As for sand soils it is suggested that a separate row should be included for “LS” indicating the appropriate ALC grade for the wetness class/FCD combination. Alternatively, the footnote to ALC Table 6 should be modified to confirm that” LS” soils will be graded as ALC Grade 2 for wetness classes I-II, except for class II where FCD are >225 when the ALC grade will be 3a. An additional table could be included for naturally calcareous soils where ALC grades will be different to non-calcareous soils. For example the soil texture and FCD combinations where ALC grade according to soil wetness differs. It would also allow the FCD groups to be reduced to four (i.e. <126, 126-175, 176-225 and >225) for parity with ALC Table 7.
ALC Table 7	Grade according to soil wetness (organic mineral and peaty soils)	The definitions of organic, mineral and peaty soils should be included just prior to the Table or as a footnote. Alternatively, where an electronic system is used a pop-up box could be used to describe organic mineral and peaty soils, along with a hyperlink to ALC Figure 3.
ALC Table 11	Soil wetness classes	The table describes the duration of waterlogging and refers to a range of conditions when the soil profile is not ‘wet’ or ‘wet’ but does not define ‘wet’. The table should be updated to include a definition of ‘wet’.

Table or Figure	Short description	Updates or modifications required
		To make the Table more user friendly the duration of waterlogging column could be split into separate columns for soils with and without a slowly permeable layer. In addition, the textural description could be replaced with columns for duration (days) and depth (cm) with and without SPL. The reference to the source data (Hodgson, in preparation) should be updated.
ALC Table 12	Wetness class of peat soils with no slowly permeable layer starting within 80 cm depth,	The soil textures that are classified as coarse (i.e. S, LS, SL, SZL and ZL) should be listed as a footnote to the Table rather than referring to those that contain <18% clay. As noted above this Table is based on limited data. More data from a wider range of drained peats is needed to substantiate the calculated FCD/soil type relationship for various soil wetness classes.
ALC Table 13	Estimation of Wetness Class of mineral or organic mineral soils with no slowly permeable layer starting within 80 cm depth but with gleying present within 70 cm,	As above
ALC Figure 2	Soil textural triangle	This should be replaced by a soil textural triangle that includes the subdivision of the CL and ZCL classes according to clay content, i.e. MCL, HCL, MZCL and HZCL. Alternatively a link to an online ALC texture class calculator could be included.
ALC Figure 3	% organic matter, clay and sand for peaty and organic mineral texture classes	See comments on ALC Table 7 (above). Also, similarly to ALC Figure 2 a link to an online organic mineral/peaty texture class calculator could be included.
ALC Figure 4	Gley colours defined according to the Munsell soil colour system	This figure has been misinterpreted by some users (Jones *et al.*, 1992). It may need redesigning or redrawing in any future iterations of the ALC guidance .

Table or Figure	Short description	Updates or modifications required
		Text prior to this Figure should include guidance on how to use a Munsell Soil Colour chart. Potentially, guidance could be included on how to use alternative methods to quantify soil colour (e.g. soil colour Apps).
ALC Figure 5	Combination of structure, texture and consistence characteristic of slowly permeable layers	The figure shows the combinations of structure, texture and consistence which are characteristic of slowly permeable layers. However, soil structure types (granular, subangular etc.), ped size (fine, medium etc) and soil consistence (e.g., firm) are not defined in the ALC, although reference is made to the Soil Survey Field Handbook (Hodgson, 1976) for more details. Updates to the ALC should include an additional figure to illustrate soil structure types/ped shape. Also, additional text to clarify ped size and confirmation of what soil textures are included in the fine to very coarse categories. A table of soil consistence categories could also be included. Alternatively, the additional information could be given through pop-up boxes or hyperlinks to relevant information or Tables/Figures.
ALC Figure 6	Flow diagram for assessing soil wetness class from FCDs, depth to gleying and depth to slowly permeable layer	A flow diagram allows the user to follow the appropriate pathway through assessments of FCD, presence/absence of slowly permeable layer or gleying, depth to SPL or gleying and soil texture to determine the relevant Table or Figure to use to assess wetness in the ALC guidance. Consider if the methodology can be simplified or supported by an online tool to improve the ALC assessment. Updates to this figure could make it more interactive so that the user is taken to the current Figure or Table. For example, in an online version of the figure the user would select the relevant characteristics of the soil/climate (e.g. <225 FCD, no SPL <80 cm, not peat and gleyed <70 cm) and they would automatically be linked to the correct Table (in this case ALC Table 13).
ALC Figure 7	Wetness class from depth to slowly permeable layer and FCDs for soils with gleying present within 40 cm	It would be necessary to include a new figure using if the FCD dataset was updated.

Table or Figure	Short description	Updates or modifications required
	depth and a slowly permeable layer starting within 80 cm depth and for peat soils with a slowly permeable layer	
ALC Figure 8	Wetness class from depth to slowly permeable layer and FCDs for soils with gleying present within 70 cm depth but not within 40 cm and a slowly permeable layer starting within 80 cm depth	As above.
New figure	Mottles	To complement the guidelines for the identification of a gleyed horizon it is suggested that any future updates to the ALC include additional text to define “mottles” and some accompanying illustrations. The SSEW field handbook (Hodgson, 1976) describes mottle contrast as *faint*, *distinct* or *prominent*. However, ALC guidelines does not specify if the mottles in the context of ALC include all three categories of mottle. This should be clarified in any subsequent revisions to ALC. Also, further guidance on the identification of the frequency of mottles noting that the important distinction for ALC purposes is to identify if there are >2% mottles.
New Figure	Example of soil structure	Including a figure to illustrate soil structure would be beneficial to help identify slowly permeable layers

Table or Figure	**Short description**	**Updates or modifications required**
New Table	Field assessment of soil consistence	An assessment of soil consistence forms part of the ALC pedotransfer function for the identification of an SPL but knowledge of soil consistence is assumed rather than described. It is suggested that a table of soil consistence categories is added to the ALC.

19 References

ADAS (1991). *Soil wetness assessment – slightly gleyed layers*. TAG Members correspondence.

ADAS (1994). *Second revision of the Agricultural Land Classification*. Report on the work carried out by ADAS under the 1993/94 Land Use Memorandum of Understanding.

ADAS (1994b). *Revised statistics for the proportions of ALC grades*. Report on the work carried out by ADAS under the 1993/94 Land Use Memorandum of Understanding.

ADAS (1995). *Second revision of the Agricultural Land Classification*. Report on the work carried out by ADAS on the spatial distribution of grade changes under the 1994/95 Land Use Memorandum of Understanding. Parts 1 and 2.

ADAS (2002). *Development of a database of agricultural drainage.* Defra Project ES0111

ADAS (2004). *To improve the process of land use planning through the development of a modern, high resolution and robust climate database for use in Agricultural Land Classification*. Defra Project LE0216.

Arnell, N.W. and Freeman, A. (2021). The effect of climate change on agro-climatic indicators in the UK. *Climate Change*. 165:40, doi.org/10.1007/s10584-021-03054-8

Avery, B.W. (1980). *Soil Classification for England and Wales (Higher Categories*). Soil Survey Technical Monograph No. 14. Harpenden.

Baier, W. (1973). Estimation of field workdays from the versatile soil moisture budget. Canadian *Journal of Engineering*. 45, 276-284.

Baier, W., Boisvert, J.B. and Dyer, J.A. (2000). *The Versatile Soil Moisture Budget (VB) Reference Manual [Computer Software]*, ECORC Contribution No. 001553. Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre. Agriculture and Agri-Food Canada, Ottawa, Ottawa, ON.

Baumgardner, M.F., Silva, L.R., Biehl, L.L. and Stoner, E.R. (1985). Reflectance properties of soils. *Advances in Agronomy.* 38, 1-44

Bell, F.G. (1985). *Engineering properties of soils and rocks*. Second Edition. Butterworth & Co (Publishers) Ltd.

Bibby J.S., Douglas, H.A., Thomasson, A.J. and Robertson, J.S. (1991). *Land Capability Classification for Agriculture.* Macaulay Land Use Research Institute.

Blavet, D., Leprun, J.C., Mathe, E. and Pansu, M. (2002). *Soil colour variables as simple indicators of the duration of soil waterlogging in a West African catena*. In: Proceedings of the 17th World Congress of Soil Science. Thailand, 1333, 1-11.

Bock, M., Gasser, P-Y., Pettapiece, W.W., Brierley, A.J., Bootsma, A., Schut, P., Neilsen, D. and Smith, C.A.S. (2018). The land suitability rating system is a spatial planning tool to assess crop suitability in Canada. *Frontiers in Environmental Science*. 6:77. doi:10.3389/fenvs.2018.00077

Boden, A.G. (2005). *Bodenkundliche Kartieranleitung* (KA5), 5th Edition. Hannover, 432 pp.

Bosma, W.J.P., Marinussen, M.P.J.C. and van der Zee, S.E.A.T.M. (1994). Simulation and areal interpolation of reactive solute transport. *Geoderma*. 62, 217-231.

Brady, N.C. (1984). *The Nature and Properties of Soils*. 9th Edition. Macmillan, New York.

Brown, I. (2017). Climate change and soil wetness limitations for agriculture: Spatial risk assessment framework with application to Scotland. *Geoderma*. 285, 173-184.

Brown, I. and Castellazzi, M. (2014). Changes in climate variability with reference to land quality and agriculture in Scotland. *International Journal of Biometeorology*. DOI 10.1007/s00484-014-0882-9

Brown, I., Towers, W., Rivington, M. and Black, H.I.J. (2008). Influence of climate change on agricultural land-use potential: adapting and updating the land capability system for Scotland. *Climate Research*. 37, 43-57.

Burnham, C.P., Avery, B.W., Findlay, D.C. and Mackney, D. (1980). The soils of England and Wales. *Field Studies.* 5, 349-363.

Carranza, C., Benninga, H-J., van der Velde, R. and van der Ploeg, M. (2019). Monitoring agricultural field trafficability using Sentinel-1. *Agricultural Water Management*. 224, 105698

Cavazza, L., Patruno, A. and Cirillo, E. (2007). Field capacity in soils with a yearly oscillating water table. *Biosystems Engineering*. 98, 364-370.

Chaplot, V., Walter, C. and Curmi, P. (2000). Improving soil hydromorphy prediction according to DEM resolution and available pedological data. *Geoderma*. 97, 405-422.

Chipanshi, A., Fitzmaurice, J., De Jong, R., Bogdan, D., Lewis, M., Kroetsch, D. and Lee, D. (2018). Assessment of soil trafficability across the agricultural region of the Canadian Prairies with the gridded climate data set. *Soil & Tillage Research*. 184, 128-141.

Clayden, B. and Hewitt, A. E, (1989). *Horizon notation for New Zealand soils*. DSIR, Division of Land and Soil Sciences. Report 1.

Davies, D.B., Eagle, D.J. and Finney, J.B. (1972). *Soil Management*. Farming Press Ltd., Fenton House, Wharfedale Road, Ipswich, Suffolk. ISBN 0 85236 025 8. 254pp.

de Castro Raulino, G.T., de Sousa Oliveira, L., do Nascimento, Í.V., da Silva, C.P., Lobato, M.G.R., Alencar, D.L., Toma., R.S., da Silva, F.G. and Mota, J.C.A. (2021). Assessing the soil colour by traditional method and a smartphone: a comparison. *Revista de Ciencias Agricolas*. 38, 75-85.

Dexter, A.R. and Bird N.R.A. (2001). Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. *Soil & Tillage Research*. 57, 203-212.

Earl, R. (1997). Prediction of trafficability and workability from soil moisture deficit. *Soil & Tillage Research*. 40, 155-168.

Edwards, G., White, D.R., Munkholm, L.J., Sørensen, C.G, and Lamandéc, M. (2016). Modelling the readiness of soil for different methods of tillage. *Soil & Tillage Research*. 155, 339-350.

Evans, C.V. and Franzmeier, D.P. (1988). Colour index values to represent wetness and aeration in some Indiana soils. *Geoderma*. 41, 353-368.

Field, M. (1983). *Creating the Complete Agromet Database*. Agricultural Memorandum 983 (unpublished paper), Meteorological Office.

Gómez-Robledo, L., López-Ruiz, N., Melgosa, M., Palma, A.J., Capitán-Vallvey, L.F. and Sánchez-Marañón, M. (2013). Using the mobile phone as Munsell soil-colour sensor: An experiment under controlled illumination conditions. *Computers and Electronics in Agriculture*. 99, 200-208.

Grose, C.J. (Ed.) (1999). *Guidelines for the classification of agricultural land in Tasmania*. Department of Primary Industries, Water and Environment, Tasmania.

Hill, K., Hodgkinson, R., Harris, D. and Newell Price, P. (2018). *Field drainage guide. Principles, installations and maintenance.* AHDB.

Hodgson, J.M. (1976). *Soil Survey Field Handbook. Describing and sampling soil profiles*. Second Edition. Technical Monograph No. 5. Soil Survey of England and Wales.

Hodgson, J.M. (Ed.) (2022). *Soil Survey Field Handbook*. Soil Survey Technical Monograph No. 5, Cranfield.

Hodgson, J.M. and Avery, B.W. (1985). *Soil Survey Field Handbook. Describing and sampling soil profiles. Second Edition with minor amendments*. Technical Monograph No. 5. Soil Survey of England and Wales.

Hollis, J.M. (1987). *The prediction of soil wetness class from soil and site properties*. Soil Survey and Land Research Centre.

Hollis, J.M. (1989). *A methodology for predicting soil wetness class from soil and site properties*. SSLRC Research Report MAFF Project c (ii). MAFF.

Holman, I.P., Hollis, J.M., Bramley, M.E. and Thompson, T.R.E. (2003). The contribution of soil structural degradation to catchment flooding; a preliminary investigation of the 2000 floods in England and Wales. *Hydrology and Earth Systems Sciences*. 7, 754-765.

Horticulture Research International (2008). *Vulnerability of UK agriculture to extreme events*. Defra Project ACO301.

Hudson, G. and Birnie, R.V. (2000). A method of land evaluation including year to year weather variability. *Agricultural and Forest Meteorology*. 101, 203-216.

Jones, R.J.A. (1985). The field capacity dataset of the Soil Survey of England and Wales: an aid to assessing soil wetness. *Soil Survey and Land Evaluation*. 5, 1-12

Jones, R.J.A. (2010). *Workability assessment for areas with natural handicap in the UK*. Cranfield University.

Jones, R.J. A. and Thomasson, A.J. (1985). *An agro-climatic database for England and Wales*. Soil Survey Technical Monograph No. 16. Soil Survey of England and Wales.

Jones, R.J.A. and Thomasson, A.J. (1993). *Effects of soil-climate-system interactions on the sustainability of land use: a European perspective*. In: Kimble, J.M. Utilization of Soil Survey Information for Sustainable Land Use. Proceedings of the Eighth International Soil Management Workshop. May 1993, 39-52. USDA Soil Conservation Service, National Soil Survey.

Jones, I.P., Watson, M.R., Hooper, A.J. (1992). *Agricultural Land Classification of England and Wales. Instruction Manual (ADAS Internal Use Only*). ADAS

Jones, R.J.A., Schulte, R., Fealy, R. and Bouraoui, F. (2014). Criterion 3 bis Excess soil moisture condition. In: Van Orshoven, J., Terres, J-M. and Tóth, T. (Eds.) *Updated common bio-physical criteria to define natural constraints for agriculture in Europe*. *Definition and scientific justification for the common biophysical criteria*; Technical Factsheets. European Commission, Joint Research Centre.

Keay, C.A. and Hannam, J. (2020). *The effect of climate change on Agricultural Land Classification (ALC) in Wales.* Capability, Suitability & Climate Programme. Welsh Government

Keay, C.A., Jones, R.J.A., Procter, C., Chapman, V., Barrie, I., Nias, I., Smith, S. and Astbury, S. (2014). *SP1104 the Impact of climate change on the capability of land for agriculture as defined by the Agricultural Land Classification*. Defra.

Leterme, B., Vanclooster, M., van der Linden, A.M.A., Tiktak, A. and Rounsevell, M.D.A. (2007). The consequences of interpolating or calculating first on the simulation of pesticide leaching at the regional scale. *Geoderma.* 137, 414-425.

Lynn, I.H., Manderson, A.K., Page, M.J., Harmsworth, G.R., Eyles, G.O., Douglas, G.B., Mackay, A.D. and Newsome, P.J.F. (2009). *Land Use Capability Survey Handbook – a New Zealand handbook for the classification of land*. 3rd Edition. AgResearch Ltd.

MAFF (1966). *Agricultural Land Classification*. Technical Report No. 11, Agricultural Land Service

MAFF (1976). *Agricultural Land Classification of England and Wales. The definition and identification of sub-grades within Grade 3*. Technical Report No. 11.1, Agricultural Land Service

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

McVicar, T.R, and Jupp, D.L.B (2002). *A 'calculate then interpolate' approach to monitoring regional moisture availability*. In: McVicar, T.R., Li Rui, Walker, J., Fitzpatrick, R.W. and Liu Changming (Eds.), Regional Water and Soil Assessment for Managing Sustainable Agriculture in China and Australia, ACIAR Monograph No. 84, 258–276.

Meteorological Office (1989). *Climatological data for Agricultural Land Classification*. *Grid point datasets of climatic variables, at 5 km intervals, for England and Wales.* Meteorological Office, Bracknell.

Met Office (2018). *State of the UK climate 2017: Supplementary report on climate extremes*. Met Office, National Climate Information Centre.

Ministry of Housing, Communities & Local Government (2021). *National Planning Policy Framework*.

Moritsuka, N., Kawamura, K., Tsujimoto, Y., Rabenarivo, M., Andriamananjara, A., Rakotoson, T. and Razafimbelo, T. (2019). Comparison of visual and instrumental measurements of soil colour with different low-cost colorimeters, *Soil Science and Plant Nutrition*. 65:6, 605-615.

Mueller, L., Schindler, U., Behrendt, A., Eulenstein, F. and Dannowski, R. (2007). *The Muencheberg Soil Quality Rating (SQR). Field manual for detecting and assessing properties and limitations of soils for cropping and grazing.* Leibniz-Zentrum fuer Agrarlandschaftsforschung (ZALF).

Müller, L., Lipiec, J., Kornecki, T.S. and Gebhardt, S. (2011). *Trafficability and workability of soils*. In: Gliński, J., Horabik, J. and Lipiec, J. (Eds.), Encyclopaedia of Agrophysics. Springer.

Müller, L. and Schindler, U. (1999). Soil moisture and workability of heavy arable soils. *Archives of Agronomy and Soil Science.* 44, 161-174

Obour, P.B., Lamandé, M., Edwards, G., Sørensen, C.G and Munkholm, L.J. (2017). Predicting soil workability and fragmentation in tillage: a review. *Soil Use and Management*. 33, 288-298.

Perry, M. and Hollis, D. (2005). The development of a new set of long-term climate averages for the UK. *International Journal of Climatology*. 25, 1023-1039.

Petelkau, H. (1984). *Auswirkungen von Schadverdichtungen auf Bodeneigenschaften und Pflanzenertrag sowie Massnahmen zu ihrer Minderung*. Tagungsbericht-Akademie der Landwirtschaftswissenschaften D.D.R. Berlin, 215, 39–48.

Pettapiece, W.W. (Ed.) (1995). *Land Suitability Rating System for Agricultural Crops. 1. Spring-seeded small grains*. A technical report prepared by Agronomic Interpretations Working Group. Technical Bulletin 1995-6E. Centre for Land and Biological Resources Research.

Post, D.F., Bryant, R.B., Batchily, A.K., Huete, A.R., Levine, S.J., Mays, M.D. and Escadafal, R. (1993). *Correlations between field and laboratory measurements of soil colour.* In: Bigham, M. and Ciolkosz, E.J. (Eds.). Soil Colour. Soil Science Society of America Special Publications.

Ragg, J.M., Jones, R.J.A., and Proctor, M.E. (1988). The refinement and representation of spatial data in an information system using statistical and DBMS procedures and trend surface analysis. Geologisches Jahrbuch. A104, 295-308. Hannover.

Reilly, J.M. (2002). *Agriculture: the potential consequences of climate variability and change for the United States*. Cambridge University Press, Cambridge.

Rivington, M., Matthews, K.B., Buchan, K., Miller, D.G., Bellocchi, G. and Russell, G. (2013). Climate change impacts and adaptation scope for agriculture indicated by agro-meteorological metrics. *Agricultural Systems*. 114, 15-31.

Robson, J.D. and Thomasson A.J. (1977). *Soil water regimes*. Soil Survey Technical Monograph No. 11

Rollett, A.J. and Williams, J.R (2019). ALC Technical Review (Part 1). Report SPEP2018-19/12. Welsh Government

Rollett, A.J. and Williams, J.R (2020). ALC Technical Review Part 2: Climate, site and interactive limitations. Report SPEP2019-20/04. Welsh Government

Rollett, A.J. and Williams, J.R (2021). ALC Technical Review Part 3; Droughtiness. Report SPEP2020-21/12. Welsh Government

Rossiter, D. (2014). *Criterion 3 Limited soil drainage*. In: Van Orshoven, J., Terres, J-M. and Tóth, T. (Eds.) (2014). Updated common bio-physical criteria to define natural constraints for agriculture in Europe. Definition and scientific justification for the common biophysical criteria; Technical Factsheets. European Commission, Joint Research Centre.

Rounsevell, M.D.A. (1993). A review of soil workability models and their limitations in temperate regions. *Soil Use and Management*. 9, 15-21.

Shaxson, F. and Barber, R. (2003). *Optimising soil moisture for plant production. The significance of soil porosity*. FAO Soils Bulletin 79.

Shields, J.A., St Arnaud, R.J., Paul, E.A. and Clayton, J.S. (1966). Measurement of soil colour. *Canadian Journal of Soil Science*. 46, 83-90.

Smith, L.P. (1967). *Potential transpiration*. MAFF, Technical Bulletin No. 16. HMSO, London,

Smith, L.P. and Trafford, B.D. (1976). *Climate and drainage*. MAFF, Technical Bulletin No. 34. HMSO, London, 119pp.

Spoor, G. (1975). *Fundamental aspects of cultivation*. In: MAFF Tech. Bulletin 29: Soil Physical Conditions and Crop Production. Proceedings of a Conference organised by the Soil Scientists of the Agricultural Development and Advisory Service, January 3-5, 1972: pp. 128-144.

Thomasson, A.J. (Ed.) (1975). *Soils and field drainage.* Soil Survey Technical Monograph No 7.

Thomasson, A.J. (1982). *Soil and climatic aspects of workability and trafficability*. 9th Conference of the International Soil Tillage Research Organisation (ISTRO), Osijek, Yugoslavia, pp. 551-557.

Thomasson, A.J. and Jones, R.J.A. (1989). *Computer mapping of soil trafficability in the UK*. In: Agriculture: Computerisation of Land Use Data. 97-109, EUR 11151 EN, Luxembourg.

Torrent, J., Schwertmann, U., Fechter, H. and Alferez, F. (1983). Quantitative relationships between soil colour and hematite content. *Soil Science*. 136, 354-358.

Tóth, B., Weynants, M., Nemes, A., Makó, A., Bilas, G. and Tóth, G. (2015). New generation of hydraulic pedotransfer functions for Europe. *European Journal of Soil Science*. 66, 226-238.

USDA (1951). *Soil Survey Manual.* United States Department of Agriculture. Handbook No.18.

USDA (1961). *Land Capability Classification*. United States Department of Agriculture. Handbook No. 210.

USDA (2004). *Saturated hydraulic conductivity: Water movement concepts and class history*. USDA Natural Resources Conservation Service.

USDA (2009). *Hydrologic soil groups*. Chapter 7. Part 630 National Engineering Handbook.

USDA. (2017). *Soil Survey Manual*. United States Department of Agriculture Handbook No. 18.

USDA (2018). *Field indicators of hydric soils in the United States. A guide for identifying and delineating hydric soils*. Version 8.2. United States Department of Agriculture. Natural Resources Conservation Service in cooperation with the National Technical Committee for hydric soils.

Van Orshoven, J., Terres, J-M. and Tóth, T. (Eds.) (2014). *Updated common bio-physical criteria to define natural constraints for agriculture in Europe*. *Definition and scientific justification for the common biophysical criteria*; Technical Factsheets. European Commission, Joint Research Centre.

Veihmeyer, F.J. and Hendrickson, A.H. (1931). The moisture equivalent as a measure of the field capacity of soils. *Soil Science*. 32, 181-193.

Webb, T.H. and Wilson, A.D. (1995). *A manual of land characteristics for evaluation of rural land*. Landcare Research Science Series No. 10. Manaaki Whenua Press.

Welsh Government (2021). *Planning Policy Wales*. Edition 11. February 2021.