2018-19 Soil Policy Evidence Programme

ALC Technical Review (Part 1)

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Soil Policy Evidence Programme

SPEP2018-19/12: ALC Technical Review (Part 1)

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Executive Summary

Introduction

- The Agricultural Land Classification of England and Wales (ALC) provides a framework for classifying agricultural land into six classes (ALC grades 1, 2, 3a, 3b, 4 and 5) according to the extent that climatic, soil and site 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.
- 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published over 30 years ago, it is possible that the threshold limits for establishing grading for some factors are no longer valid. This review assesses the evidence base to support site limitations imposed by gradient and soil limitations imposed by soil stoniness, depth and texture (Table I).

Table I. ALC limits for gradients, stones and soil depth

ALC Grade	Gradient limits (degrees)/[%]	Limiting percentages (volume of hard stones in the top 25 cm of soil		Depth limits (cm)
		Stones > 2 cm	***Stones > 6 cm***	
1	7 [12.3]	5	5	≥60
2		10	5	≥45
3a		15	10	≥30
3b	11 [19.4]	35	20	≥20
4	18 [32.5]	50	35	≥15
5	>18 [>32.5]	>50	>35	<15

- The review also investigated the methodology that is used to assess soil texture, i.e. hand texturing v laboratory methods and compared the results of the different methods of soil textural classification.

Gradient

- The gradient or slope of land has little or no direct influence on crop yields. However, the slope of land clearly affects its suitability for agricultural production; mainly through the restrictions steeper slopes impose on mechanization of crop management and on their vulnerability to soil erosion.
- With improvements in machinery design and power, along with systems that make working on a slope safer the gradient limit for ALC grade 1/2/3a could be increased to 8° (from 7°) based simply on mechanical suitability. However, the risk of soil erosion is high where slopes are >7° and soil is predominately sand or silty (i.e. sand, loamy sand, sandy loam, sandy silt loam, silt loam and silty clay loam). Thus, on balance, considering both safety and soil erosion risks, no changes to the ALC grades according to slope are recommended.

Stoniness

- In the ALC, stony soils are classified according to the relative fraction of rock fragments in soil (soil stoniness) expressed as a relative volume (Table I). The main effects of stones are to act as an impediment to cultivation, harvesting and crop growth and to cause a reduction in the available water capacity (AWC) of a soil.
- Research in other countries has suggested that the AWC of some rock types may be higher than in current ALC guidance, although this has not been quantified for rocks in Wales. Consequently, there is insufficient evidence to update the AWC values for rock listed in the ALC guidance. In addition, there is no rationale to suggest that the negative effects of stones on cultivation,

harvesting and crop quality have changed since 1988. For those reasons no changes to the ALC grades according to soil stoniness are recommended.

Soil depth

- Soil depth affects a soil's capacity to function and is an important direct and indirect determinant of crop productivity. Shallow soils can physically restrict root growth reducing plant stability and increasing the risk of lodging. Crops also respond indirectly to soil depth through the availability (or otherwise) of vital resources such as water, oxygen and nutrients. When considering the ALC grade according to soil depth it should be noted that >95% of sites would be ALC Grade 1 (i.e. ≥60 cm), if classified solely according to depth
- Soil depth can be classed as an inherent soil property unlikely to change, although erosion and change in land use may result in the removal of top soil and a reduction in total depth of soil. Soil compaction caused by vehicle or animal traffic can also cause small reductions in soil depth over time. However, given the inherent nature of soil depth and the small number of soils where soil depth is less than <60 cm (the limit for ALC Grade 1 for soil depth) no changes to ALC grade categories are recommended.

Particle size distribution

- Soil texture and structure have a major influence on water retention, water movement and aeration in soils and therefore on workability, trafficability, poaching risk and suitability as a medium for plant growth. Soil textural class is determined by the relative proportions of sand, silt and clay particles and the amount of organic matter in a soil. An assessment of soil texture can be made in the field by hand, however, accurate measurement of particle size distribution requires laboratory analysis.
- Sedimentation in water has been used as a laboratory technique to separate soil into different particle sizes for many years using either the sieve-pipette method that measures a weight concentration or the sieve-hydrometer method that measures the suspension density.
- More recently, the laser diffraction method (LDM) has become widely used. LD is an indirect optical method that is used to measure the particle size distribution according to dispersion of electromagnetic waves on the particles. It is based on the principle that particles passing through a focused laser beam at a given point of time scatter light at an angle that is directly related to their size. Diffraction angle is inversely proportional to particle size
- There is no straightforward relationship between sedimentation and laser diffraction methods. A significant difference between methods is that sedimentation methods measure mass percentage of particles (i.e. the amount of matter) and LD measures volume percentages (i.e. how much space is taken up) based on an optical diameter. Both methodologies make assumptions about the spherical shape of the soil particles, which in reality will depend upon the characteristics of an individual soil sample. For example, platy shaped grains lead to fine fraction overestimation while disc or rod shape grains result in underestimation of the 0.0001 mm to 0.100 mm range. However, it is difficult to estimate for which of the methods the error caused by the lack of sphericity is more significant.
- Recently, comparison with direct observation through digital imaging has shown that LD was a closer representation of the true particle size distribution than sedimentation based methods. However, it should be noted that the ALC and preceding Soil Survey of England and Wales work was calibrated using the pipette method and as such care would needed in moving to the LDM.

1 Introduction

The Agricultural Land Classification of 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 suitability of the land for a range of potentially suitable crops.

The ALC was 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. It was based on the United States Department of Agriculture (USDA) land capability system, which classified land into eight classes; the risks of soil damage or limitations in use are progressively greater from class I to class VIII (USDA, 1961). 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, 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. The revised system incorporated some features of the seven class Land Use Capability Classification, formerly used by the Soil Survey of England and Wales (SSEW) in which classes 5-7 broadly correspond to Grade 5 of the ALC (Bibby and Mackney, 1969). Note that although there are similarities with the Scottish system, the ALC was developed specifically for use in England and Wales. Scotland use the Macaulay Land Capability for Agriculture (LCA) classification, which was updated in the 1980s, and divides land into seven classes (with further subdivisions) depending on its potential productivity and cropping flexibility.

The final ALC grade given to a location is the lowest grade from any of the 10 criteria (i.e. criteria are combined according to the agronomic law of the minimum, Liebig's law). An expert panel review of the bio-physical criteria used to identify areas of 'severe natural constraint to agriculture' in the EU28 used a similar approach (Van Orshoven *et al*., 2014). The expert panel classified characteristics, such as soil depth or gradient, as not limiting or severely limiting; as soon as one criteria was rated as severely limiting the land was judged to present severe limitations for agricultural production. In comparison, some land classification systems are based on accumulating 'points', for example the German Muencheberg Soil Quality Rating (SQR) system (Mueller *et al*., 2007) where each indicator group (e.g. depth or slope) is scored and the final rating is based on the total score out of 100.

In 2019, 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. This review assesses the evidence base to support site limitations imposed by gradient and soil limitations imposed by soil texture, stoniness and depth.

2 Objectives

For ALC criteria in relation to gradient, soil depth and stoniness:

- Review the technical literature in relation to gradient, soil depth and stoniness.
- Assess whether the limits for each sub-grade are still relevant and correct for each criteria.
- Where appropriate, recommend new thresholds for each criteria.

For soil texture, which is a significant parameter in the assessments of droughtiness and wetness:

- Investigate the methodology that is used to assess soil texture, i.e. hand texturing v laboratory methods.
- Compare the results of different methods of soil textural classification.

3 The Agricultural Land Classification

The principal physical factors influencing agricultural production are climate, site (e.g. gradient or micro-relief) and soil. These factors, together with interactions between them, form the basis for classifying land into one of five grades; Grade 1: excellent quality to Grade 5: poor quality. Grade 3 is further divided into two sub-grades designated 3a and 3b. The top three grades (1-3a) are defined by Planning Policy Wales as the 'best and most versatile' (BMV) agricultural land (Welsh Government, 2018) and are suitable for a wide range of crops. The main limiting physical factors are identified as: climate, soil wetness, soil droughtiness, gradient, flooding, soil texture, soil depth, soil stoniness, soil chemical properties and soil erosion. The final ALC grade given to a location is the lowest grade from any of the 10 criteria (i.e. criteria are combined according to the agronomic law of the minimum, Liebig's law).

Grade 1 land is located in small pockets of lowland North East and South Wales (Figure 1). Similarly, Grade 2 land is mainly located in lowland North and South Wales, Anglesey and Pembrokeshire. Grade 3 land is more widely distributed and is located in low lying coastal and inland areas, river valleys (e.g. the Wye and Severn) and along the Welsh/English border. Finally, Grade 4 and 5 agricultural land is located in the central upland areas of Wales. Only agricultural land of Grade 3a and above will typically be suited to tillage and horticultural crops (MAFF, 1988).

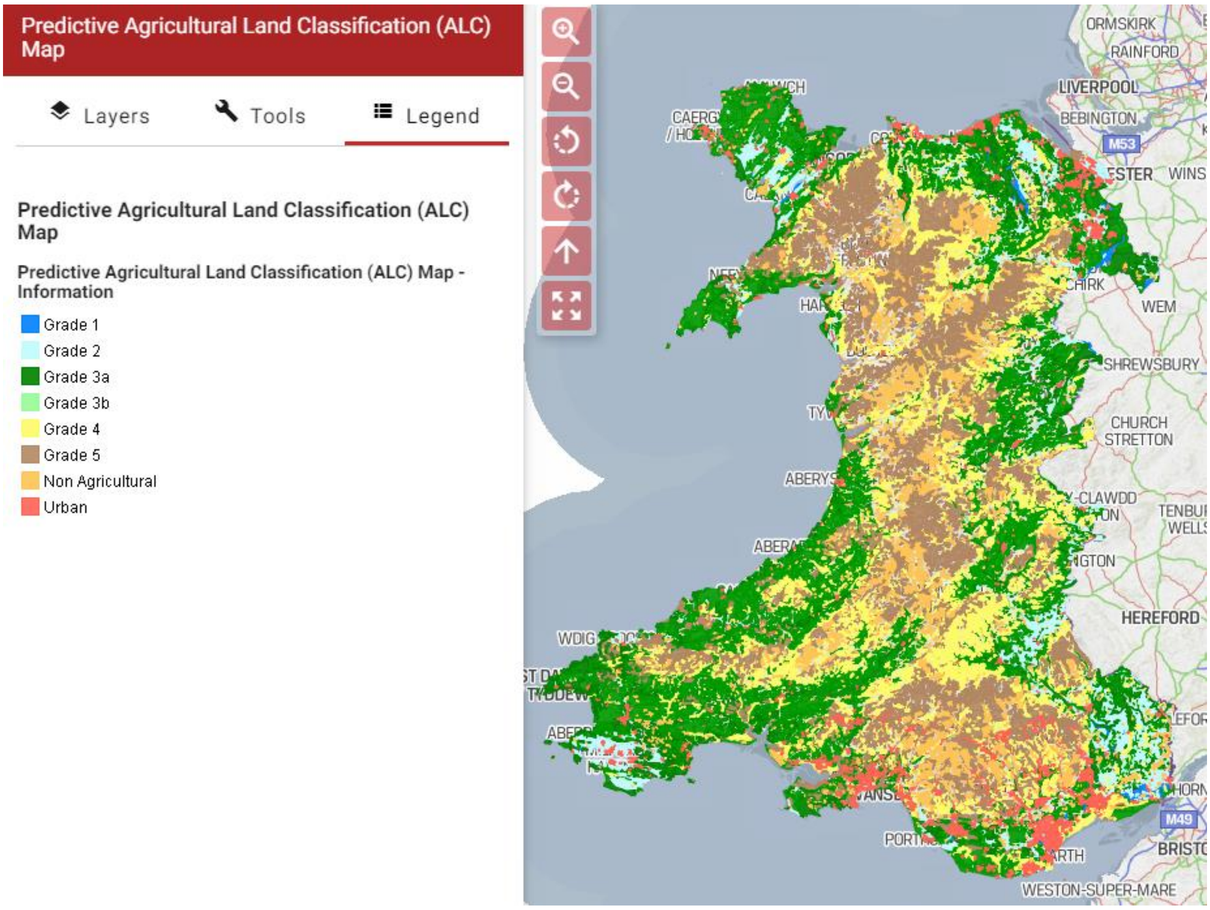


Figure 1. Predictive agricultural land classification (ALC) map[1].

[1] http://lle.gov.wales/map/alc#m=-3.4,52.5,8&b=europa&l=908h;893h;1326;

4 Gradient or slope

The gradient or slope of land has little or no direct influence on crop yields. However where slopes are steeper, land management is more challenging and the types of crop that can be grown may be limited. The current ALC gradient limits are given in Table 1. Slope is frequently used as a criterion to assess capability and suitability of land for agriculture in other land classification systems, e.g. US Soil Survey and FAO (see examples in Table 2). Sloping land makes mechanised farm operations difficult and cultivating sloping land poses an increased risk of soil erosion.

Table 1. ALC grade/subgrade according to gradient

ALC Grade/subgrade	Gradient limits (degrees)/[%]
1	7 [12.3]
2	
3a	
3b	11 [19.4]
4	18 [32.5]
5	>18 [>32.5]

Table 2. Definitions of slope classes a) US Soil Survey and b) FAO slope gradient classes.

a) US Soil Survey (Source: USDA, 2017)			
Slope Classes		**Recommended slope (gradient) class limits**	
Simple slopes	***Complex slopes***	***Lower (degrees/[%])***	***Upper (degrees/[%])***
Nearly level	Nearly level	0	2 [3]
Gently sloping	Undulating	0.6 [1]	5 [8]
Strongly sloping	Rolling	2 [4]	9 [16]
Moderately steep	Hilly	6 [10]	17 [30]
Steep	Steep	11 [20]	31 [60]
Very steep	Very steep	>24 [45]	

b) FAO slope gradient classes (Source: FAO, 2006)		
Class	**Description**	***degrees/[%])***
01	Flat	0-0.1 [0-0.2]
02	Level	0.1-0.3 [0.2-0.5]
03	Nearly level	0.3-0.6 [0.5-1.0]
04	Very gently sloping	0.6-1 [1.0-2.0]
05	Gently sloping	1-3 [2-5]
06	Sloping	3-6 [5-10]
07	Strongly sloping	6-9 [10-15]
08	Moderately steep	9-17 [15-30]
09	Steep	17-31 [30-60]
10	Very steep	>31 [60]

Van Orshoven *et al*. (2014) suggested that a steep slope (≥8.5°/15%) will start to pose problems for mechanised cultivation and that specific equipment may be required to ensure safe and effective operation. For Wales, it has been calculated that 727,600 ha (7,276 km^2) has a slope of ≥8.5°/15% of which c.70% was in utilised agricultural areas (Defra, 2010; Figure 2). Based on an utilised agricultural area of *c.*1.8 million hectare then approximately 25% of agricultural land in Wales has a slope ≥8.5°/15%.

Using data from the National Soil Inventory and Met. Office records (1921-2000) on climate, soil and site parameters Keay *et al* (2013), noted that slope was the most limiting factor at only *c*.9% of sites and that >80% of sites would be in Grade 1/2/3a for slope (i.e. slope ≤7°), Figure 3.

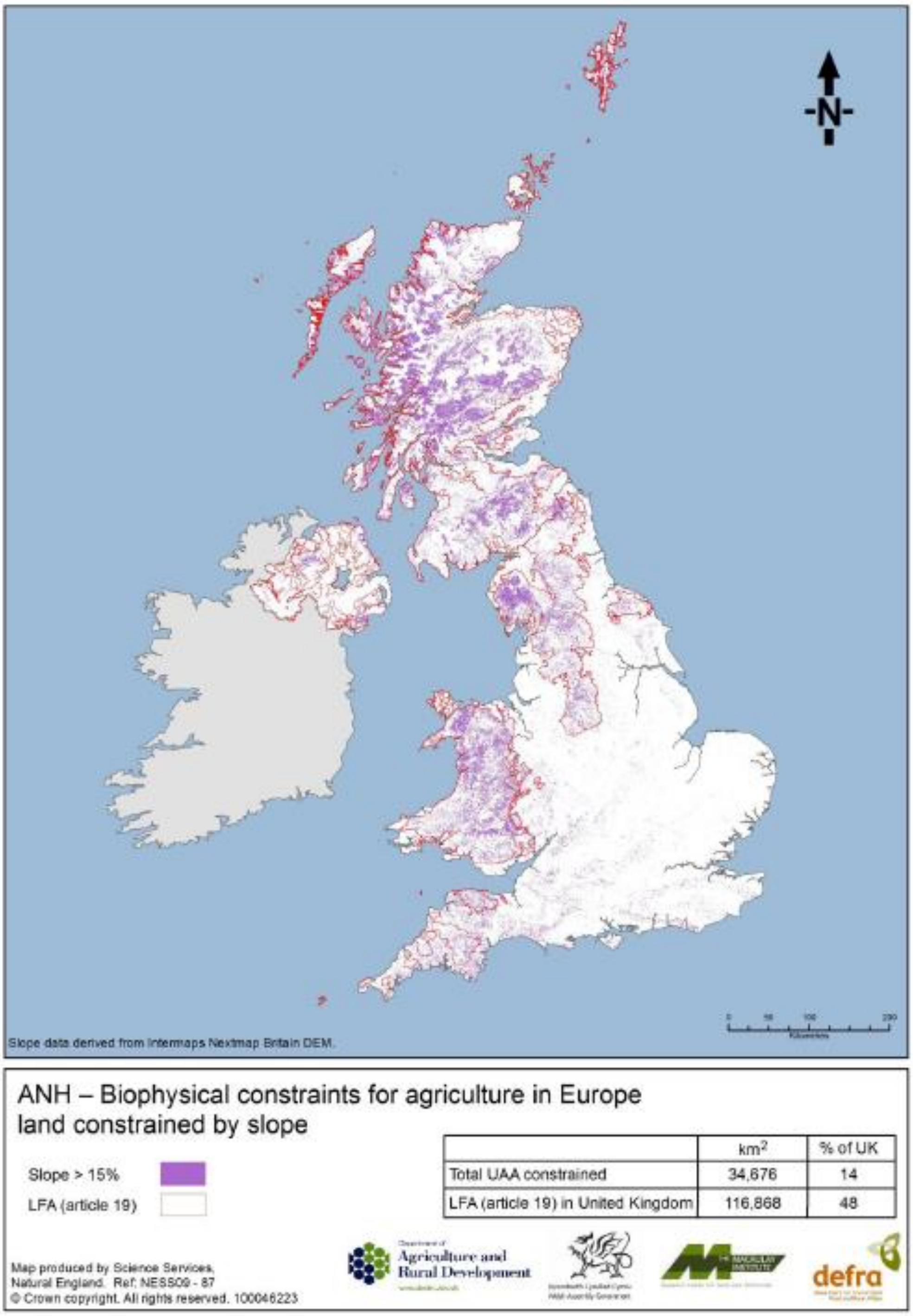


Figure 2. Slopes >15% (8.5°) in the UK. Source: Defra, 2010.

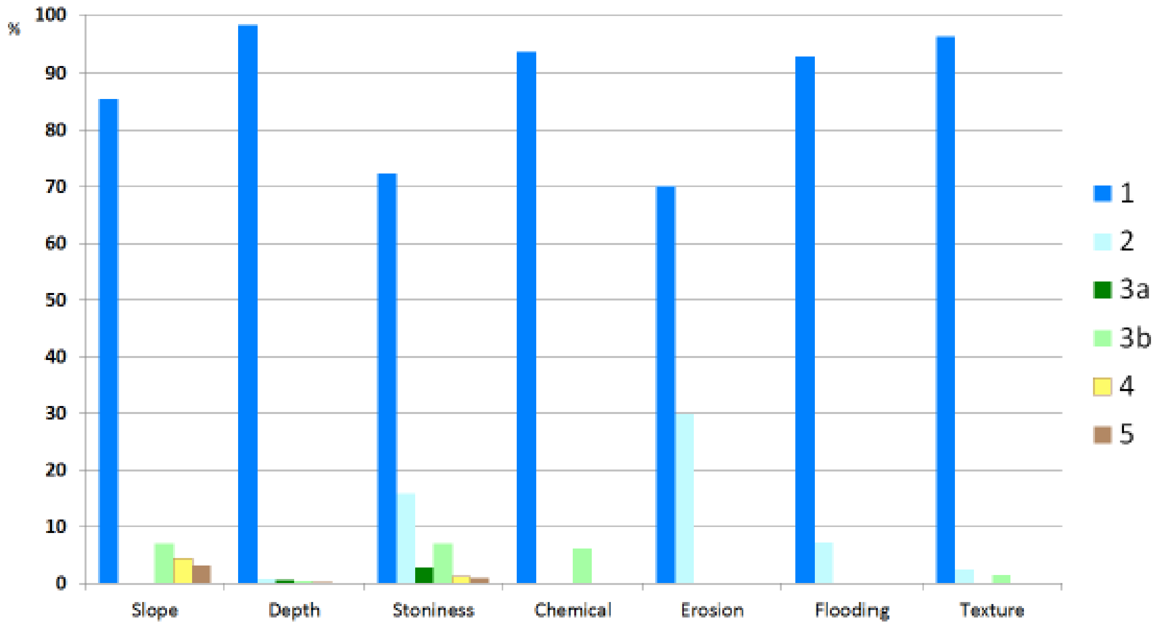


Figure 3. Proportion of land in England and Wales assigned to each ALC grade according to non-climate criteria (1921-2000). Source: Keay *et al*., 2013.

4.1 Machinery operation

Slope has a significant effect on mechanised farm operations since most conventional agricultural machinery performs best on level ground and steep slopes are not readily accessible for farm machinery (Baker and Capel, 2011). The safe and efficient use of machinery on sloping land depends on the type and design of the machine and on the nature of the slope being farmed. For example, slopes with adequate turning space at the top and bottom may be negotiated safely whereas similar slopes without turning space may not. Weather (i.e. rainfall and wind speed), ground condition (e.g. wet, muddy or frosty), ground cover and surface roughness will also affect machinery operation on sloping land.

The current ALC limits according to gradient are given in Table 1 above and are based primarily on safe limits for a two-wheel 90 horsepower (hp) tractor. However, two-wheel drive tractors are now uncommon; it was estimated in 2010, that <1% of tractors that were sold in that year were two-wheel drive[2]. In addition, in 2018, the average horsepower of a tractor was around 165 hp[3], almost twice that of the tractor on which the grade's limits were originally based.

Four-wheel tractors have more traction than two-wheel tractors and can often continue to work where two-wheel vehicle would suffer from wheel slip. They are likely to be safer than two-wheel tractors on slopes, although the risk of tractors and equipment turning over is greater and work rates are less efficient than on level ground. A high proportion of accidents with tractors are associated with overturning or tipping over (e.g. 55% in a recent Austrian study by Mayrhofer *et al*., 2014). Mayrhofer *et al*. (2014) analysis of accident reports showed that overturning and tip-over accidents with tractors often occurred on steep slopes and adjacent embankments and ridges. Modern machinery may also include features that make operation on slopes more efficient and safer, e.g. combines with hillside

[2] https://www.fwi.co.uk/machinery/so-who-uses-two-wheel-drive-tractors
[3] https://aea.uk.com/industry-insight/tractor-statistics/

levelling systems that can operate on slopes up to 15° (28%)[4]. In addition, Daccache *et al*., 2012 have suggested that a slope of 8.5° is the limit for potato de-stoning, planting and harvesting machinery.

The bearing strength (effectively the weight a soil can withstand before severe damage occurs to the structure of the soil) of the topsoil is also critical in the safe operation of machinery on slopes. Where surfaces have a low bearing strength the safe angle for working is reduced. The structural strength of soil is a dynamic characteristic, which for a particular soil varies widely according to soil moisture content and all soils lose structural stability when wet. Also, soil texture determines how easily soil particles are rearranged when certain stress is applied. Soils with a high proportion of silt or fine sand are inherently weakly structured.

4.2 Soil erosion

The factors that influence the vulnerability of land to soil erosion have been reviewed extensively in the literature. Risk factors include the intensity, duration and timing of rainfall events; the physical, biological and chemical properties of soils; the length, gradient and form of slope; the type of vegetation/crop on the land and its stage of development; and the type and timing of land management practices (Knox *et al*., 2015).

Erosion can occur as a result of water runoff, wind blow, tillage, co-extraction with root vegetables and farm machinery, and human and animal impact (from recreation and grazing) (Knox *et al*., 2015). In general, water-induced erosion is more widespread than wind erosion (Owens *et al*., 2006). It occurs most frequently on sloping land with bare soil or sparse crop cover where the soil is weakly structured and has a fine sandy or coarse silty texture. The presence of stones reduces erosion risk to some extent as it can protect the soil surface from the impact of rain, which can loosen soil particles and can slow overland flow and prevent soil detachment by wind blow.

Steeper slopes are often associated with shallower soils, with less water retention capacity due to gravity and with a higher risk for soil degradation (erosion) and landslides (Van Orshoven *et al*., 2014). Steepness of slope in combination with soil texture affects the level of risk of soil erosion by overland flow (Defra, 2005). In general, sandy and light soils are at most risk of erosion even on gentle slopes (2-3°) where rills may develop in some seasons during very wet periods (Table 3). In comparison, the risk of erosion on heavy soils is lower because of their greater inherent stability, even when the slope is steep (>7°). In addition, slope gradient, form and length affect the volume and velocity of overland flow which influences the rate/amount of eroded and transported material (Knox *et al*., 2015).

Table 3. Risk of erosion in relation to slope steepness and soil texture (Defra, 2005).

Soil	**Steep slope >7°**	**Moderate slope 3-7°**	**Gentle slope 2-3°**	**Level ground <2°**
Sand	Very high[1]	High[2]	Moderate[3]	Lower[4]
Loamy sand	Very high	High	Moderate	Lower
Sandy loam	Very high	High	Moderate	Lower
Sandy silt loam	Very high	High	Moderate	Lower
Silt loam	Very high	High	Moderate	Lower
Silty clay loam	High	Moderate	Lower	Slight
Other mineral soils	Lower	Lower	Slight	Slight

[1]Very high risk: rills are likely to form in most years and gullies may develop in very wet periods. [2]High risk: Rills are likely to develop in most seasons during wet periods. [3]Moderate risk: Sediment may be seen running to roads, ditches or watercourses and rills may develop in some seasons during very wet periods. [4]Low risk: Sediment rarely seen to move but polluting runoff may enter ditches or water courses. Slight risk: any water running off the site is unlikely to be discoloured.

[4] http://www.hillcotechnologies.com/products.html

4.3 Conclusions for ALC grades for slope.

Slope of land clearly affects its suitability for agricultural production; mainly through the restrictions steeper slopes impose on mechanization of crop management and on their vulnerability to soil erosion. Note that the old Land Use Capability Classification recommended that only land with a slope of 0-3° was classified as Class 1 and that more moderately sloping land (3-7°) should be categorised as Class 2 (Bibby and Mackney, 1969). The more restrictive grading was due to the effects of slope on mechanised farming at that time (1960s) which are no longer a constraint in the present day. Most modern day machinery can operate safely and efficiently on a slope of ≤7°. Indeed, with improvements in machinery design and power, along with systems that make working on a slope safer the gradient limit for ALC grade 1/2/3a could be increased to 8°. However, the risk of soil erosion is high where slopes are >7° and soil is predominately sand or silty (i.e. sand, loamy sand, sandy loam, sandy silt loam, silt loam and silty clay loam). This may reduce the range of crops that can be grown or markedly increase production costs. For other mineral soils, the risk of soil erosion is low, even at slope of >7°. On balance, considering both safety and soil erosion risks, no changes to the ALC grades according to slope are recommended. However, it is recommended that ALC guidance notes the high risk of erosion on light soil types when the slope gradient is >3°.

5 Soil stoniness

Stony soils are usually classified according to the relative fraction of rock fragments in soil (soil stoniness) expressed as a relative volume or a relative mass. The main effects of stones are to act as an impediment to cultivation, harvesting and crop growth and to cause a reduction in the available water capacity of a soil. The degree of limitation imposed by stones depends on their quantity, size, shape and hardness. ALC specifies size limits for stones that will not pass through sieves with 2 or 6 cm square mesh; either size class can be most limiting and determine the grade (Table 4). Grade limits have been specified for stones retained on a 6 cm sieve because they usually have a more detrimental effect than smaller stones. Small numbers of large boulders or stones which can be removed easily are ignored when allocating the ALC grade according to stoniness. Stones smaller than 2 cm, which have no or only minor effects on cultivation, should also be ignored, although large amounts of small gravels will make soils unsuitable for many root crops. Where the stones are of soft lithology, such as soft chalk, weakly cemented sandstones or siltstones, the limits are reduced by one grade or subgrade.

Table 4. ALC grade according to stoniness

Grade/subgrade	**Limiting percentages (volume of hard stones in the top 25 cm of soil**	
	Stones > 2 cm	***Stones > 6 cm***
1	5	5
2	10	5
3a	15	10
3b	35	20
4	50	35
5	>50	>35

Van Orshoven *et al*. (2014) suggest that soil texture is severely limiting to crop growth if the volume of coarse fragments of any kind in topsoil is 15% or more, including rock outcrops, boulders or large boulders. Similarly, the limit for Grade 3a land is 15% (by volume in the top 25 cm of the soil) for stones >2 cm, although the limit value for larger stones is only 10%.

5.1 *Machinery operation*

Large numbers of stones will prevent tillage and small stones wear on tillage implements, damage cultivation and harvesting equipment and can effect crop growth, most notably for root crops such as potatoes and carrots. Production costs may also be increased due to the extra wear and tear on equipment. In addition, crop establishment may be poorer in stony soils, and crop quality may be reduced as a result of impediment to rooting leading to poor establishment and restricted nutrient and water uptake. Root crops are particularly susceptible to damage on stony soils. For example, carrots may become mis-shaped (e.g. forked) as they grow around stones, trailing crops such as courgettes may be damaged by stones on the soil surface and potatoes may become bruised during harvesting. Injuries to potato tubers, reduces tuber quality and increases storage rot (Saini and Grant 1980).

For root crops, stone separation and burying will be required to avoid root damage and malformation. Stone separation is the process of removing stones from the formed ridges, and burying them between alternate rows. This substantially reduces tuber damage during harvesting, and greatly increases harvester output[5]. Small stones can be removed easily by destoning providing they do not exceed 10% (volume). Soils with >15% stones > 6 cm diameter in the top 25 cm are unsuitable for potato production (Knox *et al*., 2011). Similarly, soils with a high content of gravel that cannot be removed are unsuitable.

5.2 *Available water capacity*

Stones directly reduce the volume of soil exploitable by roots, thus reducing water-holding capacity and nutrient supply. Therefore, as the stone content of a soil increases there will be a concurrent increase in droughtiness. Van Orshoven *et al*. (2014) report that >15% coarse fragments (defined as >2 mm) reduce water-holding capacity by at least 40%, exacerbating seasonal droughts in most European climates. More recently, Hlaváĉiková *et al*. (2018) reported that the presence of rock fragments in a moderate-to-stony soil decreased the soil water storage by 23% or more and affected the soil water dynamics. In contrast, soil water retention may increase significantly with increasing volume of stones exhibiting high porosity such as with chalk (Parajuli, 2018).

Coarse fragments can help aerate and heat the soil by adsorbing energy from the sun, provide paths for rapid water entry, and slow runoff (Van Orshoven *et al*., 2014). Field soil thermal regimes showed that soil temperature increased with increasing coarse fragment content (Chow *et al*., 2007). Sensitivity to erosion is increased by the removal of stones from soils e.g., de-stoning for potato cultivation (Boardman, 2013). Conversely, as soils become stonier through long-term erosion they become more stable and less susceptible to soil loss.

The suggested values for the available water in different rock published in ALC are tentative and based on limited evidence (MAFF, 1988). Total available water in stones and rock ranged from 1% (hard rocks or stones) to 10% (chalk or chalk stones); for the same rock types easily available water ranges from 0.5 to 7% (MAFF, 1988). More recently, Tetegan *et al*., 2011, analysed around 1,900 pebble/gravel samples from different locations, mainly in the central part of France, to determine physical and hydric properties. The available water content of each pebble was calculated by using the difference between the water content at field capacity and the water content at wilting point. The water content of the various rock types at field capacity was: chalk (21%), Chert (13%), flint (6%), Gaize (31%) and limestone (9%). The water content at field capacity (Wfc) was very close to the water content at -100 hPa (W-100); a linear relationship between W-100 and W-15840 (wilting point) was used to derive the available water content of the rock. For example, the AWC of chalk was calculated as 14%. In addition, Rempe and Dietrich (2018), have suggested that deep weathered bedrock capable of storing plant-available moisture is common but unquantified. They reported that up to 27% of the annual rainfall

[5] https://www.teagasc.ie/crops/crops/potatoes/agronomy-potatoes/planting-and-cultivation/

at a site in northern California, was stored as rock moisture (defined as: the exchangeable water stored in the unsaturated zone of weathered bedrock).

5.3 Conclusions for ALC grades for stoniness.

Although, the AWC of some stones may be >10% (e.g. chalk), many hard stones are unlikely to contribute significantly to the available water in soil as they contain no pores capable of holding water. Although, some research in other countries (e.g. Tetegan *et al.,* 2011; Rempe and Dietrich, 2018 reported above) has suggested that the AWC of some rock types may be higher than reported by MAFF (1988) this has not been quantified for rocks in Wales. Currently, there is insufficient evidence to update the AWC values for rock listed in the ALC guidance. In addition, there is no rationale to suggest that the negative effects of stones on cultivation, harvesting and crop quality have reduced since 1988. For those reasons no changes to the ALC grades according to soil stoniness are recommended.

6 Soil depth

Soil depth affects a soil's capacity to function and is an important direct and indirect determinant of crop productivity. Shallow soils can physically restrict root growth reducing plant stability and increasing the risk of lodging. Crops also respond indirectly to soil depth through the availability (or otherwise) of vital resources such as water, oxygen and nutrients, which is also determined by soil depth.

Standard tillage depth is typically 15-25 cm so that soils that are shallower than this depth will have limited cropping options. Limiting depths in the ALC are given for soil overlying consolidated or fragmented rock which cannot be penetrated by cultivation implements (Table 5). For comparison, soil depths used in the Land Use Capability Classes (LUC) in New Zealand are given in Table 6; the minimum soil depths for LUCs 2 and 3 are broadly similar to those in ALC grades 2 and 3b.

Table 5. ALC, limiting depths for soil overlying consolidated or fragmented rock (MAFF, 1988)

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

Table 6. New Zealand Land Use Capability Class (Lynn *et al*., 2009).

Land Use Class	Soil depth (cm)	Description
1	>90	Deep
2	45-90	Moderate
3	20-45	Shallow
4-8	<20	Very shallow

6.1 *Soil depth and available water*

Water will be rapidly depleted from shallow depths and soil depth is a major factor in determining available water capacity (AWC). AWC can be defined as the water that is available to support plant growth. It is the difference between the soil water content at field capacity (the point when all the pores that drain under gravity are empty) and permanent wilting point (i.e. the point where water cannot be extracted from the soil by plant roots) (ADAS, 2007). The volume of available water in a soil varies according to the number and size distribution of pores in the soil which is controlled by soil structural condition, texture and organic matter content. Total AWC is the average AWC (i.e. soil water content between 0.05 and 15 bar suction and 0.10 and 15 bar for loamy sands) for each horizon based on texture, stoniness and thickness of horizon and the depth of rooting. A shallow soil over consolidated or fragmented rock (other than chalk) is unlikely to hold sufficient water necessary to meet crop demand when transpiration greatly exceeds precipitation e.g. during summer months and additional water from summer rainfall events or irrigation is required to support crop growth.

The easily available water capacity of soils (i.e. soil water content between 0.05 and 2 bar suction and 0.10 and 2 bar for loamy sands) is used within ALC to account for reduction in a roots ability to extract water as efficiently at depth in the soil. Soil texture is also important with shallow sandy soils holding less water than a silty or loamy soil of the same depth (Table 7).

Table 7. Available water storage capacity of soil according to textural class[6]

Textural Class	Available water storage capacity (mm water/m soil)
Clay	200
Clay loam	200
Silt loam	208
Clay loam	200
Loam	175
Fine sandy loam	142
Sandy loam	125
Loamy sand	100
Sand	83

6.2 *Different measurements of soil depth*

The total soil depth is often defined as the depth of soil to the parent material. However, from a productivity perspective the plant root system also requires an effective depth of soil over which to forage for water and nutrients i.e. its working depth (Rickson *et al.*, 2012). Effective soil depth, is lower than total soil depth and may be limited by the depth to rock, slowly permeable horizon, gley or iron pan; total soil depth and depth to rock are compared in Figure 4.

[6] http://www.droughtmanagement.info/literature/BC_MA_Soil_Water_Storage_Capacity_2005.pdf

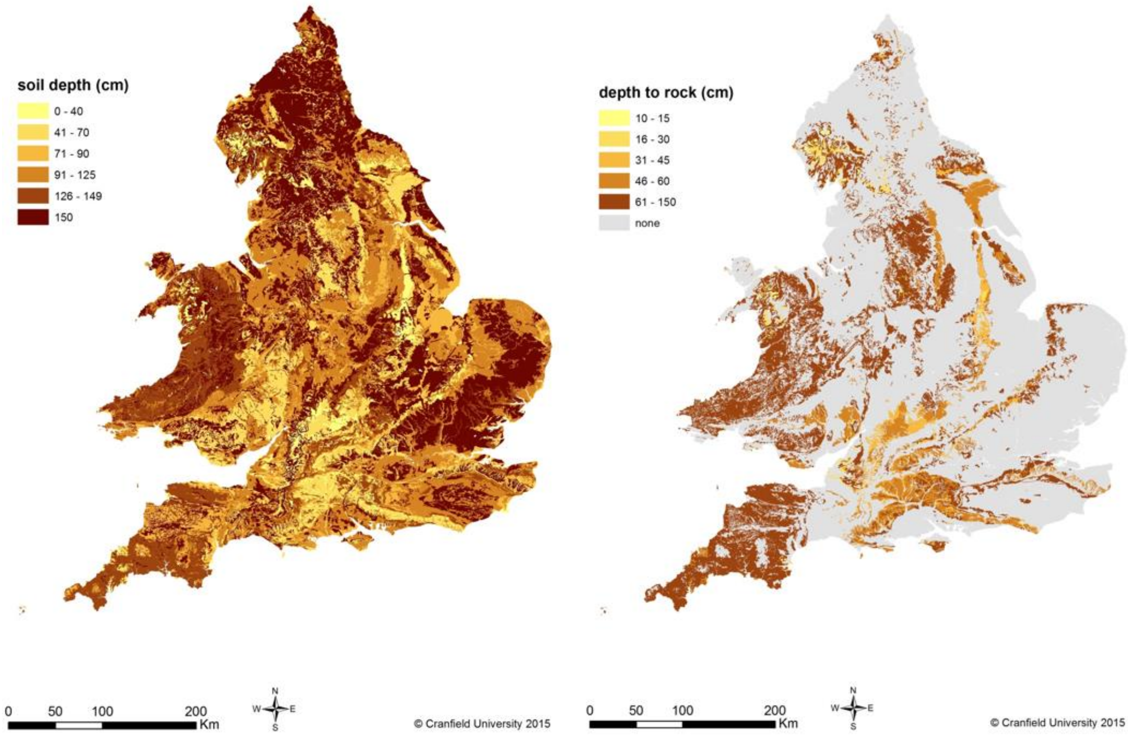


Figure 4. Soil a) total and b) depth to rock (none: no rock present at depth up to 150 cm). Source: Rickson *et al*. (2017).

Effective depth relates to plant growth and is defined as the vertical distance into the soil from the surface to a layer that prevents further downward growth of plant roots (rock, compacted layer, hardpans and plough pans). In terms of hydrological soil functions, the impact of effective depth varies seasonally. Rooting depth defines the effective soil depth taking into account any barriers to root extension. Most crops root to about 1 m, although Fan *et al*. (2016) showed that at least half of the root biomass could be found in the upper 20 cm of soil for all crops (Table 8).

Table 8. Range of root depths (cm) (Fan *et al*. 2016)

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

6.3 Conclusions for ALC grades for soil depth.

Van Orshoven *et al*. (2014) suggest two limiting soil depths of ≤15cm (very severe limitations) and ≤30cm (severe limitations), Table 9. The severely limiting depth of 30 cm proposed by Van Orshoven *et al* (2014) corresponds to the limit values for ALC grade 3a; any soil with a depth of <30 cm cannot be graded as BMV. Similarly, Rickson *et al*. (2012) suggest that two soil depths can be distinguished: the critical and the crucial soil depth. The critical depth is a limit to cultivation whereas the crucial depth is the limit to plant growth. They define the critical depth as the soil depth in which plant cover achieves values above 40%, which has been reported as between 25-30 cm. The crucial depth is much lower and depends on the parent material on which the soil was formed. The critical depth of 25-30 cm is again in line with the value for ALC grade 3a.

Table 9. Limitations in physical rooting depths. Source: Van Orshoven *et al.*, 2014.

Physical rooting depth	Limitation
≤ 15cm	Normal tillage is impossible and short dry periods will cause severe water stress.
≤ 30cm	Water stress is likely to occur in most environments with an actively-growing crop. This depth of soil severely limits crop growth.

When considering the ALC grade according to soil depth it should be noted that most soils would be ALC Grade 1, if classified solely according to depth. Using data from the National Soil Inventory and Met. Office records (1921-2000) on climate, soil and site parameters Keay *et al*. (2013), noted that slope was the most limiting factor at <1% of sites and that >95% of sites would be in Grade 1 for soil depth (i.e. ≥60 cm), (Figure 5). In addition, Rickson *et al.* (2012) noted that where shallow soils (<30 cm in total depth) dominated soil series, these associations accounted for *c*.2% of the land area of England and Wales.

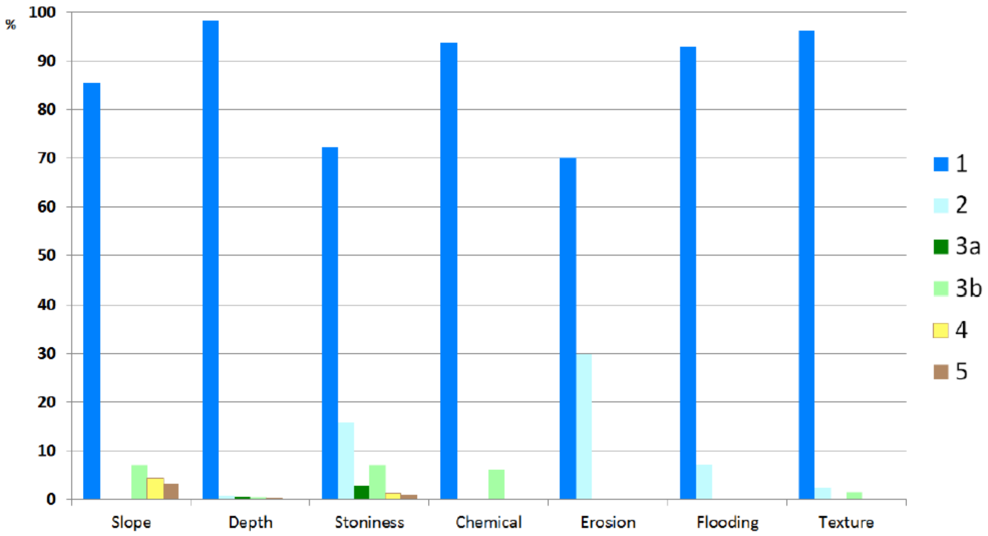


Figure 5. Proportion of land in England and Wales assigned to each ALC grade for non-climatic factors. Source: Keay *et al.*, 2013.

Soil depth can be classed as an inherent soil property unlikely to change, although erosion and change in land use may result in the removal of top soil and a reduction in total depth of soil. Soil compaction caused by vehicle or animal traffic can also cause small reductions in soil depth over time. However, given the inherent nature of soil depth and the small number of soils where soil depth is less than <60 cm (the limit for ALC Grade 1 for soil depth) no changes to ALC grade categories are recommended.

7 Particle size distribution

Soil texture and structure have a major influence on water retention, water movement and aeration in soils and therefore on workability, trafficability, poaching risk and suitability as a medium for plant growth (MAFF, 1988). Soil textural class is determined by the relative proportions of sand, silt and clay particles and the amount of organic matter in a soil. It may be measured in a laboratory by particle size analysis or in the field by hand texturing. Particle size fractions that are used in the UK to determine soil texture are in Table 10 below.

Table 10. ALC particle size fractions

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 6).

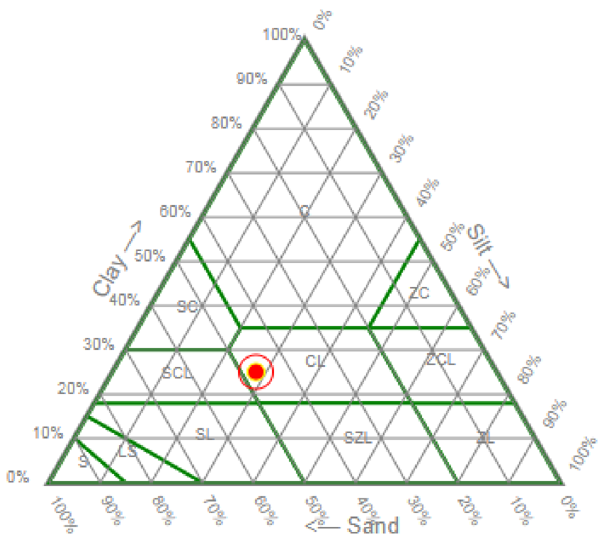


Figure 6. Soil textural triangle: particle size class estimator (available online at http://www.landis.org.uk/services/tools.cfm)

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 for 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.

For ALC, grading according to soil wetness requires an assessment based on wetness class, field capacity days and soil texture of the top 25 cm. Wetness classes are further sub-divided into four groups according to soil texture based on the ease of cultivation:

1. Sand, loamy sand, sandy loam and sandy silt loam;

2. Silty loam, medium silty clay loam, medium clay loam and sandy clay loam,

3. Heavy silty clay loam and heavy clay loam

4. Sandy clay, silty clay and clay.

Note: medium sub-classes of clay loam and silty clay loam have <27% clay content.

Texture is also a key parameter for estimating the available water capacity of a soil profile. Coarser sandy soils are very susceptible to drought stress in dry periods. Soils with sand topsoils are not eligible for ALC grades 1, 2 or 3a and those with loamy sand topsoils are not eligible for Grade 1 reflecting their low water holding capacity.

7.1 Hand texturing to assess soil texture

Accurate measurement of particle size distribution requires laboratory analysis but can be time consuming and expensive. However, an assessment of soil texture can be made in the field by hand, although debates about the comparability of lab and hand texturing is ongoing (see Section 7.3 for details) This requires about a dessert spoonful of moist[7] soil which is kneaded until soil crumbs are broken down and the soil texture can be determined by the feel of the soil using the key in Figure 7.

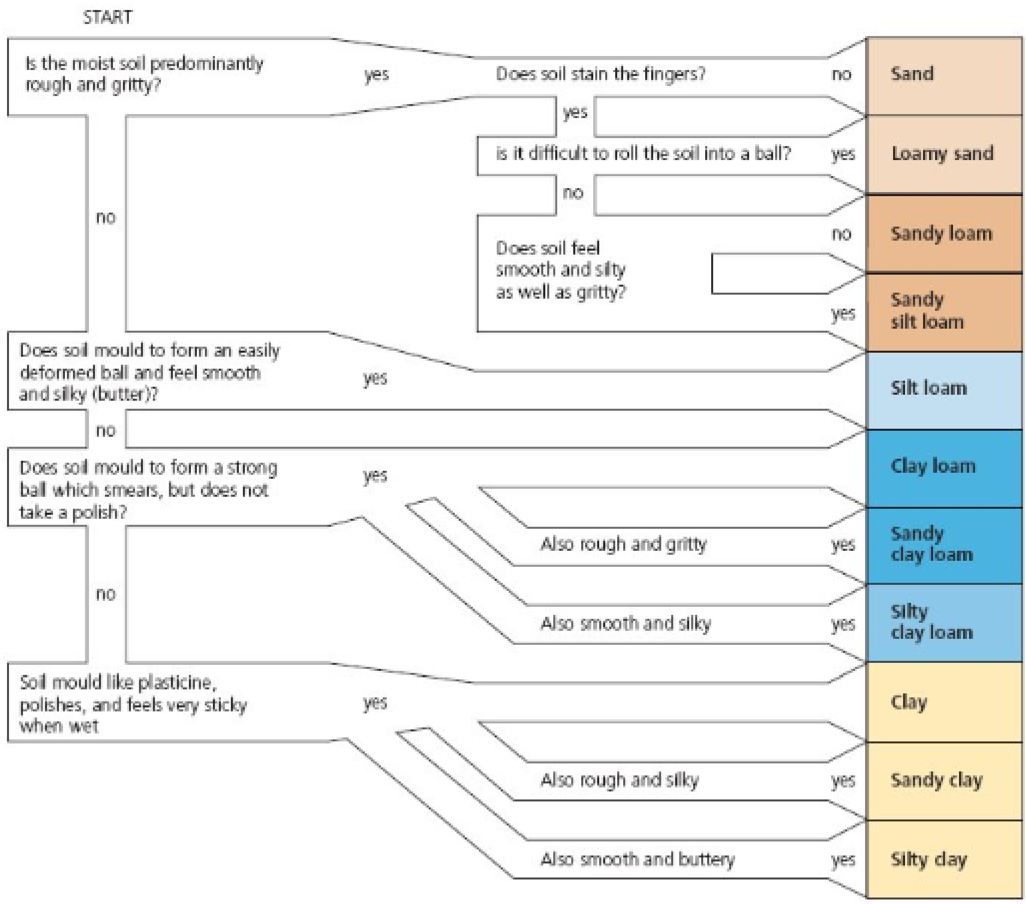


Figure 7. Guidelines for the assessment of soil texture by hand (Source: AHDB, 2017).

7.2 Particle size methodology

Soil consists of particles of various shapes and sizes, the aim of particle size analysis (PSA) is to group the particles into size classes and to determine the relative proportion by weight of each particle size

[7] Sufficient moisture is required to hold the soil together and to show its maximum stickiness.

fraction to quantify the particle size distribution (PSD). No methods quantifying PSD can serve as a universal benchmark as all methods (e.g. sedimentation, sieve, and laser diffraction) suffer from inherent biases based on particle shape, sphericity, density, chemical composition, and pre-treatment methods (Eshel, *et al*., 2004).

7.2.1 Sedimentation methods

Sedimentation in water has been used as a laboratory technique to separate soil into different particle sizes for many years. Sedimentation is typically preceded by wet sieving which aims to separate particles of sand size (0.06-2.00 mm) from silt and clay particles. Two broad sedimentation techniques for soil PSA have been developed using Stokes Law, which describes how fast (the velocity) a particle will settle as a function of its diameter and the properties of the liquid in which it is settling. The two methods are the sieve-pipette method that measures a weight concentration and the sieve-hydrometer method that measures the suspension density (Fisher *et al*., 2017). An appropriate pre-treatment typically used prior to sedimentation is to remove organic matter and carbonates and to disperse soil aggregates. Both methods are relatively time consuming and rely on the laboratory operative to perform the analysis accurately.

7.2.1.1 Pipette method

The pipette method as described in ISO 11277:2009 is accepted in many countries as the official reference method for measuring PSD. The pipette method is based on taking a small sub-sample using a pipette from a specified depth at a specified time from a sample where all particles >0.06 mm have been removed.

In the MAFF/ADAS method (1982) the organic matter in soil is first removed by oxidation with hydrogen peroxide as follows. Approximately 10 g of air dried soil (ground to pass a 2 mm mesh) is added to a beaker to which hydrogen peroxide solution is added along with a few drops of ocatan-2-ol and allowed to stand overnight at room temperature. The beaker is then placed on a hotplate and more hydrogen peroxide is added until the reaction stops. About half of the liquid is then evaporated (by increasing the hotplate temperature) before the sample is cooled. The cooled liquid is then centrifuged and the supernatant is discarded; the residue is retained for fractionation.

Dispersing reagent (sodium hexametaphosphate and anhydrous sodium carbonate) is added to the peroxide treated soil (the residue from the centrifuge) and shaken overnight. The residue is then sieved (0.063 mm) and washed before evaporating to dryness (hotplate and oven). The dry residue is passed through a nest of sieves (0.6, 0.212, 0.063 mm and a receiver) and shaken for 15 minute. The weight of residue in each sieve (equating to the coarse, medium and fine sand content, respectively) is then obtained (after drying and cooling in a desiccator). Residue from the receiver is diluted with water and left overnight at a known temperature. The sample is then stirred for 30 seconds before timing begins. A pipette is used to take an initial sample followed by second samples (at 9 cm depth) after, for example, 4 minutes 19 seconds and 7 hours 12 minutes at 20°C (sampling times vary according to sample depth and laboratory temperature). Samples are evaporated on a hotplate before oven drying, cooling in a desiccator and weighing. The following major size fractions are calculated clay (<0.002 mm) from the sample taken after >7 hours, silt, (0.002-0.063 mm) from the sample taken after > 4 hours and sand (0.063-2 mm) from the sieved sample.

7.2.1.2 Hydrometer method

Typically the sample will be dispersed using the same methodology as described for the pipette method (i.e. chemical dispersal with sodium hexametaphosphate). As organic matter is not removed prior to dispersion the method is not suitable for samples with high levels of organic matter; Jensen *et al*. (2017) noted that when SOM content was ≥2% the hydrometer method underestimated the clay content and the uncertainty increased with increasing SOM content. On completion of shaking the sample is stirred for a further 20-30 seconds before the hydrometer is immersed in the sample after around 40 seconds. Further hydrometer readings are taken after 240 and 360 minutes (although timings vary depending on the size fraction that is being measured). A reading from a blank solution is taken at the same time as from the soil suspension (this is used in the final calculation of particle size fractions).

7.2.2 Laser diffraction method

The laser diffraction method (LDM) is an indirect optical method that is used to measure the particle size distribution according to dispersion of electromagnetic waves on the particles. It is based on the principle that particles passing through a focused laser beam at a given point of time scatter light at an angle that is directly related to their size. Diffraction angle is inversely proportional to particle size.

ISO 13320:2009 provides guidance on LDM for PSA but does not address the detailed requirements of particle size measurement of specific materials. The International Standard provides guidance on instrumentation and size distribution measurements for many two-phase systems (e.g. powders, sprays, aerosols etc.) by an analysis of their light-scattering properties. The International Standard is applicable to particle sizes ranging from approximately 0.0001 mm to 3 mm, which encompasses the size fractions that are used in the UK to determine soil texture, (i.e. range from <0.002 mm (clay) to up to 2 mm (sand)) . For non-spherical particles, a size distribution is reported, where the predicted scattering pattern for the volumetric sum of spherical particles matches the measured scattering pattern. This is because the technique assumes a spherical particle shape in its optical model. The resulting particle size distribution is different from that obtained by methods based on other physical principles (e.g. sedimentation, sieving).

There is no standard technique for soil sample preparation for laser diffraction, although ultrasonic action (the application of high-frequency sonic energy to disperse aggregates) and sodium hexametaphosphate solution are widely used. Özer and Orhan (2015) compared three pre-treatment methods: 1) ultrasonic only, 2) ultrasonic and sodium hexametaphosphate and 3) sodium hexametaphosphate pre-treatment followed by ultrasonic treatment. The authors concluded that the best dispersion was obtained from the third treatment, which resulted in measurements showing a higher clay content than for the other methods; this was attributed to better separation of the fine clay particles from the coarser particles by the more vigorous dispersion method.

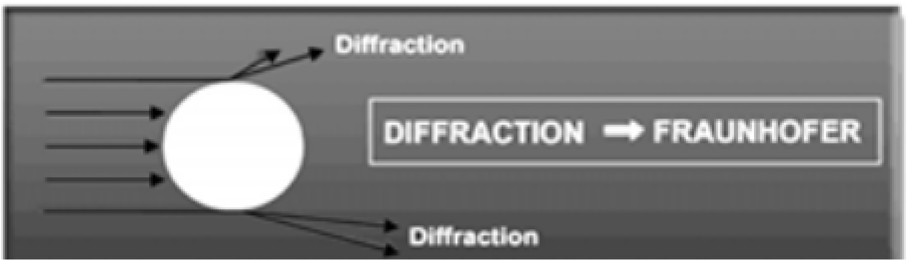
During the measurements the LD instrument should be located in a clean environment free from electrical noise, mechanical vibration, temperature fluctuations and out of direct sunlight and draughts. Any suitable optically transparent liquid of known refractive index may be used. The sample should be checked before analysis to ensure that particles have been dispersed adequately. The particle concentration in the measurement zone should be high enough to produce an adequate signal yet low enough to ensure multiple scattering is insignificant to the particle size result. The effect of multiple scattering is generally to increase the angle of scattering and, thus, to shift the size distribution results to lower sizes.

A blank measurement should be performed prior to assessment of the soil samples to check the instrument set up and to detract from the measurements taken from the soil samples. In addition, samples of a reference material should also be used to confirm that the instrument is correctly functioning.

The laser beam is passed through the suspension of soil particles and the light is scattered, at various angles. The scattering is measured by a recording device and numerical values relating to the scattering pattern are recorded for subsequent analysis. These numerical scattering values are then transformed, using an appropriate optical model and mathematical procedure, to allocate the particles to a number of discrete size classes forming a volumetric PSD.

Two different models are used for calculation of particle size distribution: the Fraunhofer and Mie model (Figure 8). The first assumes a complete diffraction of laser beams and thus no knowledge of the optical properties of an examined soil is required. The second uses the Mie model which takes into account diffraction, diffusion and absorption and requires knowledge of the refractive and absorption indices. However, there is no standard for the setting of the key parameters of refractive index and absorption value, which impact on the soil PSA results (Eshel *et al*., 2004; Ryżak and Bieganowski, 2011).

a) Fraunhofer theory



b) Mie model

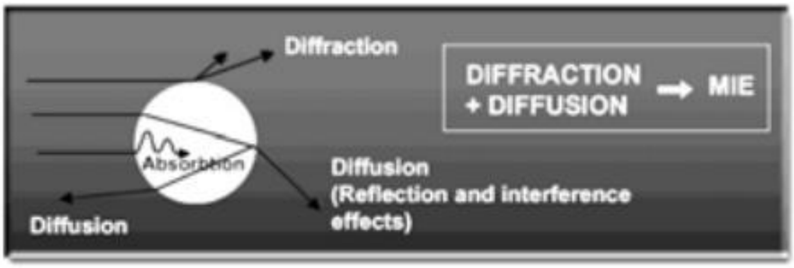


Figure 8. Behaviour of laser beam obstructed by a soil particle according to a) the Fraunhofer theory and b) the Mie model (Source: Kondrlova *et al*., 2015).

Both the Fraunhofer and Mie theories assume that the particles have a spherical shape. However, in reality, clay particles typically have a non-spherical shape. The projected cross-sectional area of a non-spherical particle averaged over all the particle's possible orientations relative to the direction of the beam is larger than that of a sphere with an equal volume (Jonasz, 1991 cited by Eshel *et al*., 2004). This may lead to the assignment of a measured particle to a larger size fraction than it actually belongs to on the basis of its apparent radius (Eshel *et al*., 2004). Hence LD can potentially underestimate the amount of clay particles in a soil sample.

According to ISO 13320, errors made in sample preparation are often the largest part of the total error and can be attributed to: non-representative sub-samples, inefficient dispersion, comminution (reduction in particle size) during dispersion, air bubbles (due to foaming dispersants or vigorous stirring) and scattering caused by changes in temperature. Another source of error is departure from theoretical assumptions, e.g. aspherical particles, rough particle surface, optical heterogeneity, fluorescence or selection of an inappropriate optical model.

Other factors that can affect the PSA obtained through the LDM, include: the sensitivity of the equipment (i.e. the number of detectors included in an instrument may vary), the choice of measurement time, and how the soil sample is prepared (e.g. Di Stefano *et al*. 2010). Sample preparation processes can include drying, grinding, mechanical dispersion (mixing by various mixers, using an ultrasonic bath) and chemical dispersion (adding of appropriate dispersant). There are also post-processing factors that can change the LDM PSD, such as the choice of Fraunhofer or Mie diffraction models to derive results from measurements or the optical parameters used (e.g. Ryżak and Bieganowski, 2011; Özer *et al*., 2010), however, it is possible to retrospectively apply alternative models to the original measurement data.

High reproducibility has been reported from repeated LD measurement on the same sample of fine-grained sediments (Sperazza *et al*., 2004, cited by Fisher *et al*. 2017). The LD technique requires a much smaller sample (e.g. 0.3-0.5 g) than sedimentation methods (e.g. 10-40 g) (Fisher *et al*., 2017). This can be an advantage when the amount of available sample is limited, however a reliable subsampling technique is critical to make sure that small samples are representative of the bulk soil. ISO 13320 suggests a rotating riffler should be used to take a sub sample for analysis. If subsampling is not done well results can vary widely, for example, Miller and Schaetzl (2012) found that when carrying out repeated measurements using LD 11.5% of the 1,485 samples they studied changed textural class between the first and second soil subsample. Working with small samples may also underestimate the coarser part of the sample, since there are very few grains represented during the measurement (Rasmussen and Dalsgaard, 2017).

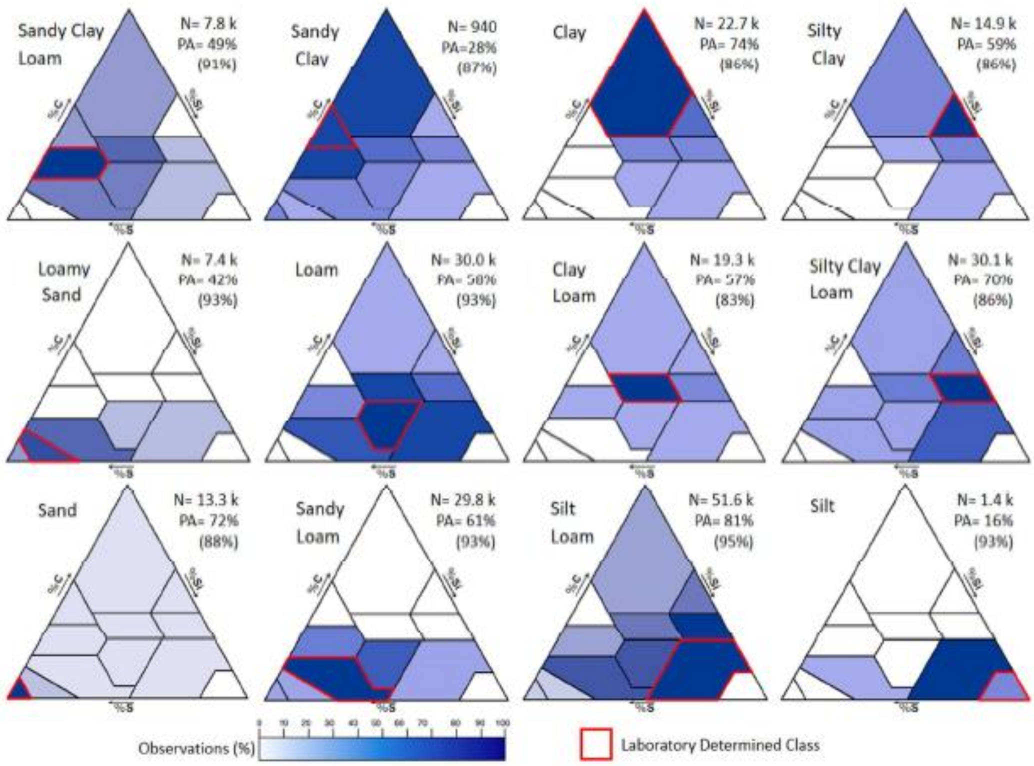
7.3 Comparison of hand texturing with laboratory determination

Debate about the comparability of results from hand texturing of soil in the field and laboratory determination of PSD has been ongoing for more than 40 years. Hodgson *et al*. (1976) compared field estimates (hand texturing) and laboratory analysis (pipette method) of the silt and clay contents of 184 soils from the west midlands regions of England. Their results showed that for 80% of samples the hand texturing assessment was within ±8% of the clay content and ±12% of the silt content determined by the pipette method. Other, studies have shown that trained soil scientists have achieved approximately 50% absolute accuracy compared to laboratory techniques for assessing particle size distribution (i.e. an exact match with the laboratory determination of soil texture class comparisons reported by Salley *et al*., 2018). However, because laboratory methods can be imprecise and at time inaccurate the maximum possible accuracy may be less than 100%.

For example, Minasny, *et al*. (2007), compared the results of hand texturing and PSD (by hydrometer or pipette) from 17,979 Australian soil samples, which showed that there was considerable difference (21-94% agreement, depending on textural class) between hand texture classes and those determined by laboratory PSD methods. More recently, Salley *et al*. (2018), compared soil texture classes (243,898 samples) determined by hand texturing by professional soil scientists and seasonal field technicians with laboratory analysis (Figure 9). Data was used from the National Cooperative Soil Survey-NCSS soil characterisation database (professional soil scientists) and a US Bureau of Land Management dataset (field technicians) where sample data was available from both hand texturing and laboratory analysis. The overall accuracy of the professional soil scientists was 66%, compared to 32% for the field technicians. When including adjacent hand texturing classes (i.e. a correct result was defined as including textural classes adjacent to the laboratory determined texture on the USDA textural triangle), accuracy increased to 91% for the soil scientists and 78% for the technicians. The overall absolute accuracy for professional soil scientists was highest where one particle-size fraction dominated the sample, such as Clay (74%) and Sand (73%) (Figure 9).

Fenton *et al*. (2015) compared initial hand texturing in the field with laboratory methods (hydrometer, pipette and laser diffraction) used to determine actual sand–silt–clay percentages of sections of the same soil profile at a grassland site in Ireland. The authors noted that at lower depths there were variations in texture between the hand textural classes and those determined by laboratory measurement. Hand texture methods identified a higher clay content than laboratory measures, which was suggested to be related to sand lenses in the lower horizons. These were described, but not included, in the hand texturing assessment but would have formed part of the bulked laboratory samples, thus causing the discrepancies in clay content. The variation in hand texturing and laboratory results at lower horizons would have resulted in different assessments of soil physical quality. For this reason Fenton *et al.* (2015) suggested that laboratory analysis, regardless of method, should be preferred to simple field assessments.

a. Professional soil scientists



b. Field technicians

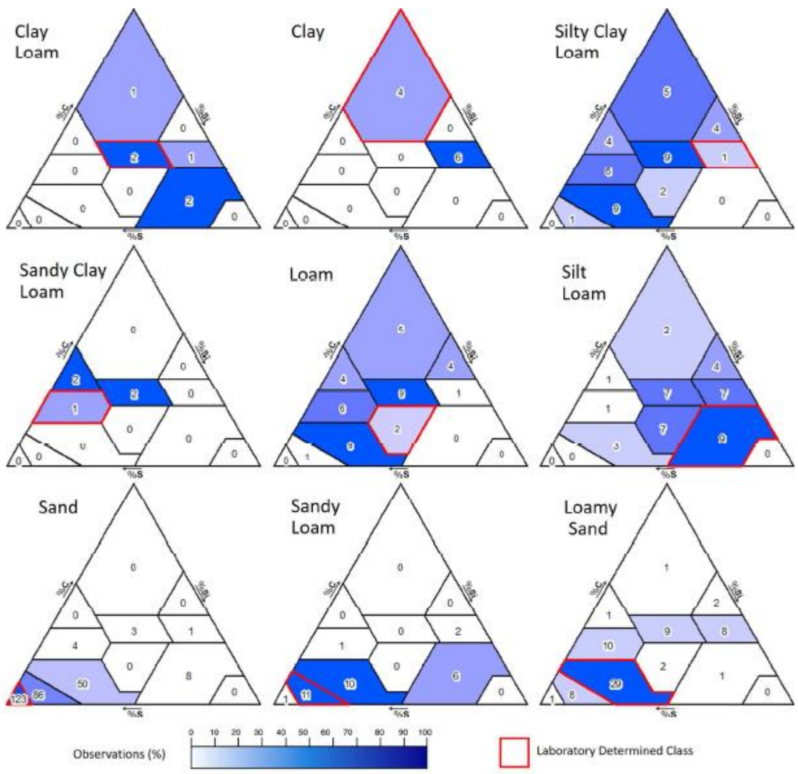


Figure 9. Classification agreements for textural classes by a) professional soil scientists and b) field technician. Red outline represents the laboratory validation texture group. For the professional scientists, N is the sample size, PA is accuracy and the value in parenthesis is the accuracy-adjacent value (Source: Salley *et al*., 2018).

7.4 Comparison of laboratory methodologies

All laboratory particle size measurement techniques attempt to represent 3-dimensional shapes using a 1-dimensional parameter. The LD technique uses an equivalent spherical volume basis, whereas the SPM uses an equivalent spherical sedimentation principle. It is therefore not unexpected that the two techniques produce differing proportions of material for a set of arbitrary thresholds, such as <0.002 mm, <0.006 mm, and <2 mm (Fisher *et al*., 2017). There are a number of publications that compare PSA methodologies, these include comparisons of sedimentation methods (e.g. pipette v hydrometer), comparisons of LDM (i.e. Fraunhofer v Mie Model) or comparisons between sedimentation and LDM. Some recent examples are discussed below.

Fenton *et al*. (2015) compared three methods (hydrometer, pipette and laser diffraction) used to determine sand–silt–clay percentages of sections of the same soil profiles at seven depth intervals. In general, there was good agreement between PSA values measured using pipette and hydrometer methods. Laser diffraction reported the same trends in soil texture through each profile, however, the proportions showed a consistent but marginal difference in value in >50% of sample comparisons. Laser diffraction consistently determined a greater proportion of clay than the pipette and hydrometer methods for both profiles for each depth interval.

Kondrlova *et al*. (2015) compared PSA using both methods of LD (i.e. Fraunhofer and Mie), using 11 different combinations of refractive and adsorption indices for the Mie model. The resulting PSD, varied depending on the combination of indices selected for the Mie model (Figure 10) and sometimes resulted in different final classifications (determined using the US soil textural triangle).

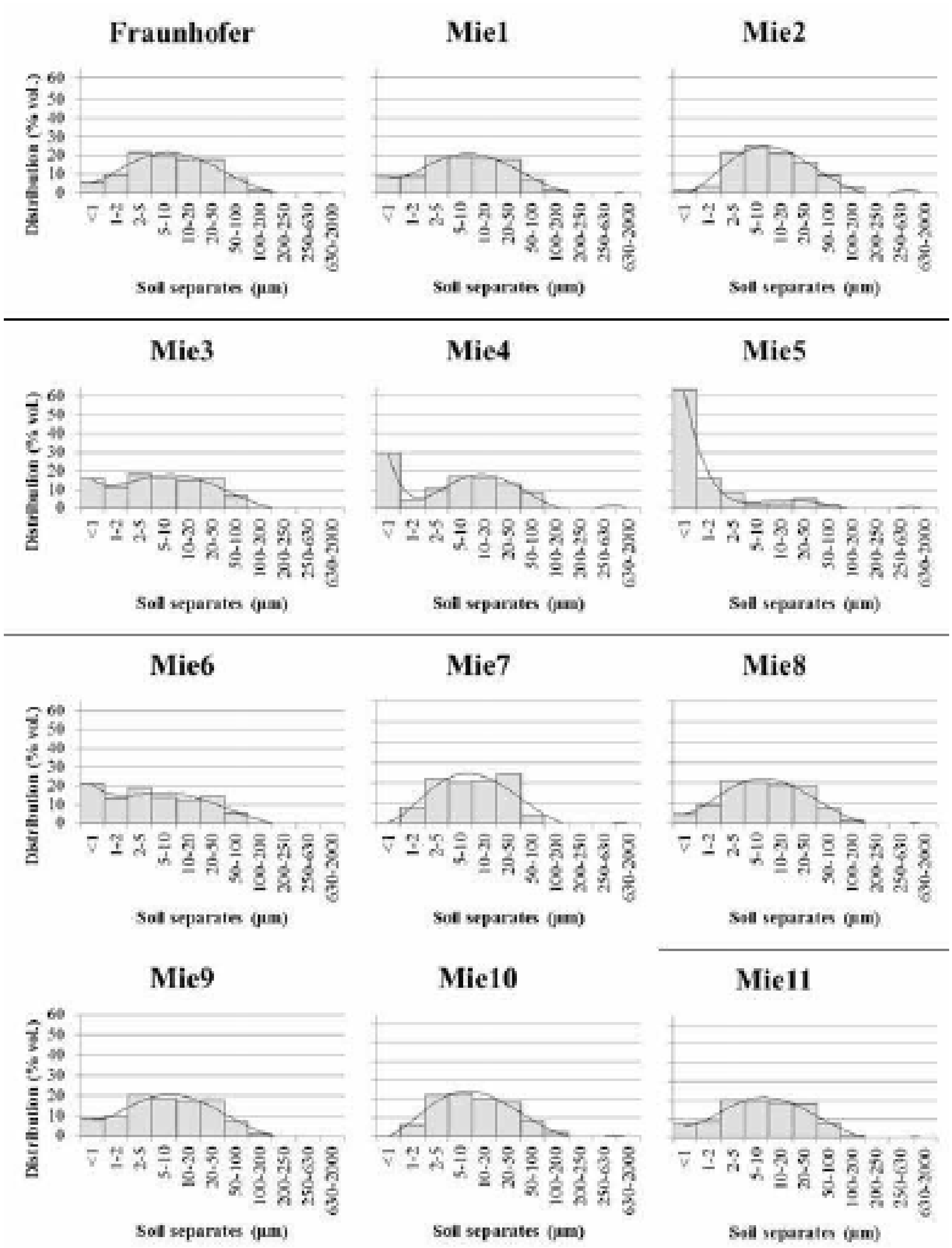


Figure 10. Volume percentage distribution of selected soil particle sizes according to various calculation algorithms for PSD estimation. Mie 1 to Mie 10 represent different combinations of refractive index and absorption index (Source: Kondrlova *et al.*, 2015).

Fisher *et al.* (2017), used the sedimentation based sieve plummet balance method (SPM) and LDM to measure the particle size distribution of 22 soil samples representing four contrasting Australian Soil Orders. The LDM samples were further sub-divided into pre-treated and not pre-treated samples; all SPM samples were pre-treated. For the pre-treatment organic matter was removed, followed by carbonates and soluble salts then rinsed with deionised water before a dispersion agent was added prior to placing in an ultrasonic bath and shaking. A comparison of the PSA for the two LD methods showed that, in most cases, there was very little difference in PSA between pre-treated and not pre-treated samples. Further data analysis showed that it was possible to relate the LDM and sedimentation data (Figure 11) using Lin's concordance correlation coefficient (CCC). The CCC measures agreement between two methods by measuring the variation of their linear relationship from the 45° line through the origin. This showed that the LDM equivalent of the SPM particle size thresholds <0.002, <0.02 and <0.2 mm were <0.009, <0.026 and <0.28 mm.

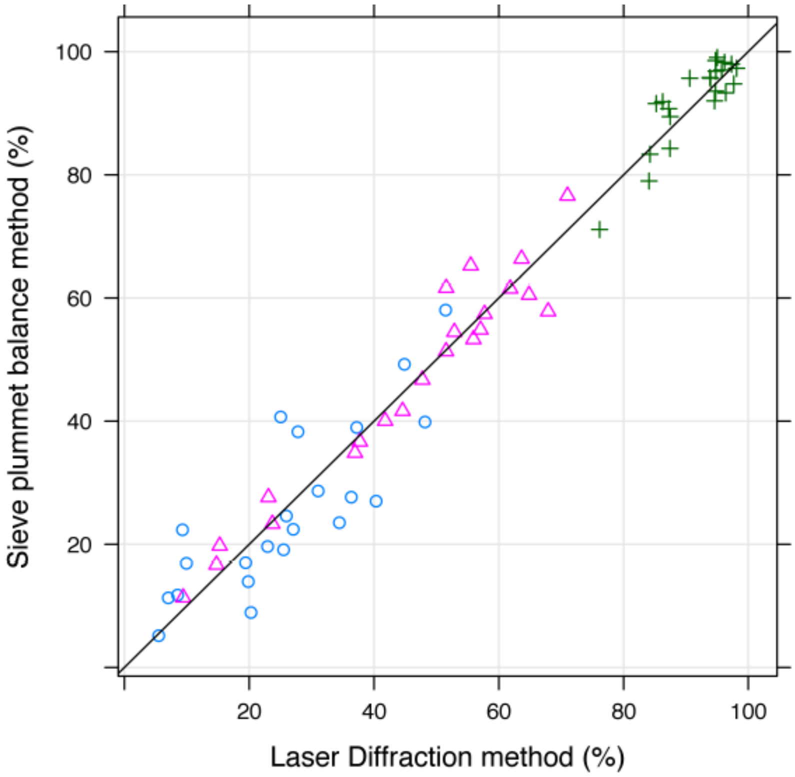


Figure 11. Scatter plot of cumulative particle size (%) using sieve plummet balance and laser diffraction. Results for LDM are without pre-treatment. Blue circles correspond to coordinates for LDM <0.009 mm (x-axis), SPM <0.002 mm (y-axis); pink triangles for LDM <0.03 mm, SPM <0.02 mm; and green crosses for LDM <0.28 mm, SPM <0.20 mm (Source: Fisher *et al.*, 2017).

Šinkovičová *et al*. (2017) compared the results of LD, using two different laser particle analysers: ANALYSETTE 22 MicroTec plus (Fritsch GmbH) and Mastersizer 2000 (Malvern Instruments Ltd) with the results obtained by pipette method for 132 soil samples from Slovakia (Figure 12). Results were compared against size fractions, which relate to the soil survey methodology groups in Slovakia: clay <0.001 mm; medium and fine dust 0.01-0.001 mm; coarse dust 0.05-0.01 mm; fine sand 0.25-0.05 mm and medium sand 2-0.25 mm. Results showed differences between both LDMs and between LD and the pipette method.

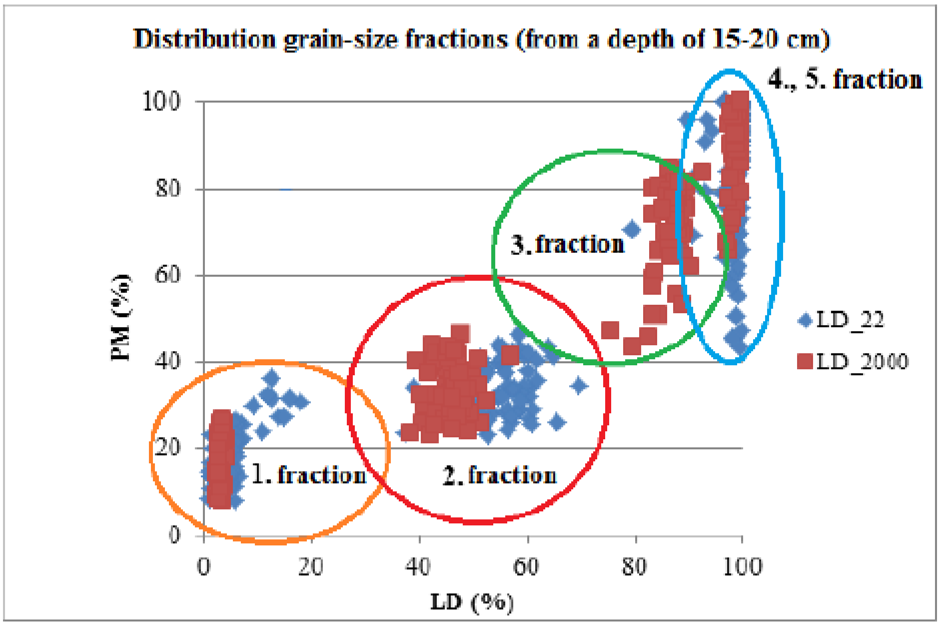


Figure 12. Comparison of PSD, as determined by laser diffraction LD) and pipette method (PM) for samples taken from a depth of 15-20 cm (Source: Šinkovičová *et al.*, 2017).

Yang *et al*. (2019) compared the PSD of soils determined using three different methods: sieve-pipette, laser diffraction and scanning electron microscope. Results from SPM-suggested that, the soil texture types were primarily silt loam, accounting for 55% of the total soil samples analysed. When using LDM almost 90% of the soil samples were classified as silt loam; however, they were mainly located in the lower portion of the classification due to lower clay contents (Figure 13). Compared with SPM, LDM underestimated the clay content by 18.9% and overestimated the silt content by 25.3%. The typically non-spherical shape of clay particles and the inconsistent particle density among particle sizes were attributed as the main causes. The discrepancies in sand, silt, and clay contents resulted in soil texture class shifts for almost half of the soil samples analysed.

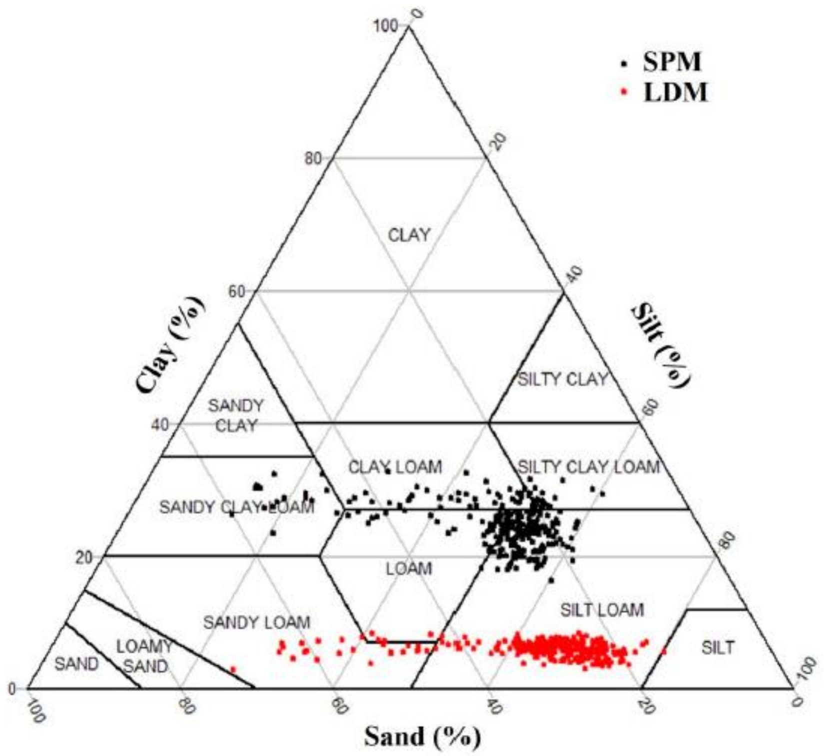


Figure 13. Soil texture of 277 soil samples determined by sieve pipette method (SPM) and laser diffraction method (LDM) displayed on a USDA soil textural triangle (Source: Yang *et al*., 2019).

Bittelli *et al.* (2019), compared particle size distribution measured by sedimentation methods (pipette and sedigraph) and LD with a digital imaging technique. The digital imaging technique measured the diameter of each particle by counting the number of pixels covered by each particle on the digital image. Automated imaging methods allow millions of particles to be photographed and analysed at various levels of magnification. The imaging technique was used as the reference (i.e. it was considered to have directly measured each particle) and compared to the other methods (based on derived properties) for determining PSD for 11 soil samples (Figure 14).

The two methods based on sedimentation (pipette and sedigraph) largely overestimated the amount of small size particles in all soils tested, in particular for soils having larger fractions of particles in the clay and fine silt range (samples 65, 143,163, 189, 216 and 221). The authors also noted that where soil particles in the <0.002 mm fraction were platy (e.g. Kaolinite) and thus deviated from the assumption of sphericity (inherent in LD and sedimentation methodologies) then the variability between methods was higher than when soil particles were spherical (e.g. Albite). Overall, assuming that direct observation through digital imaging was a closer representation of the true distribution, the authors concluded that LD provided a better estimate of PSD than sedimentation based methods; LD was recommended as the standard method for PSA in soils (Bittelli *et al*., 2019).

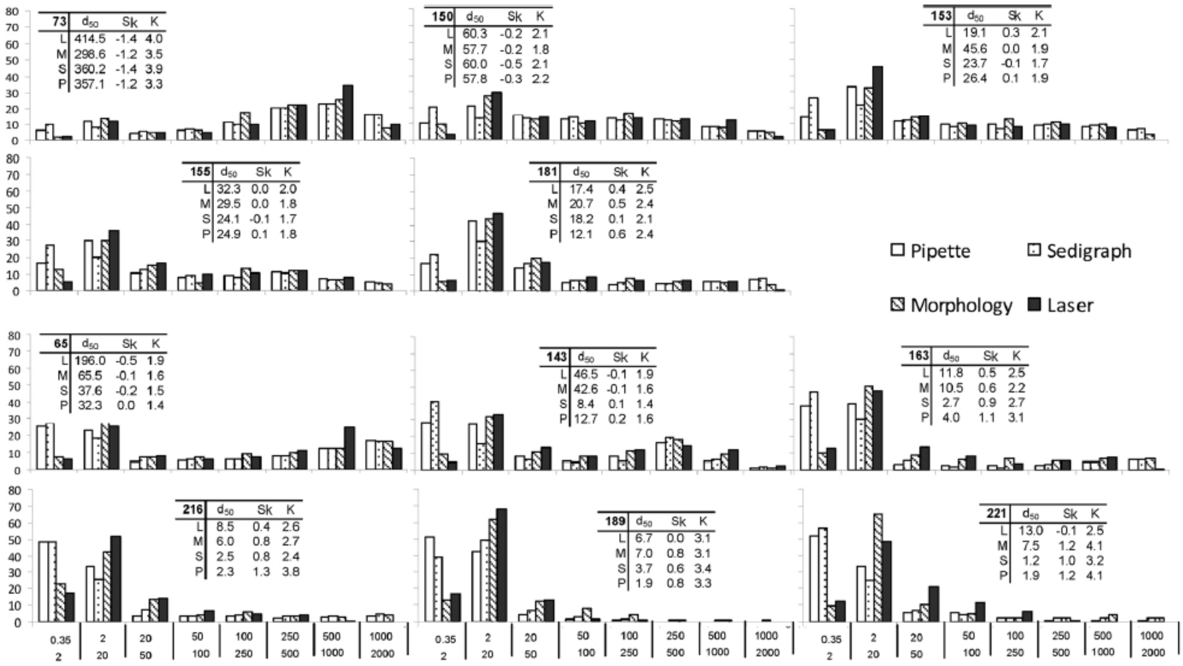


Figure 14. Particle size distribution of eight fractions for digital imaging (M), laser (L), pipette (P) and sedigraph (S) methodologies. SK: skewness (degree of distortion from the normal distribution), K: kurtosis (measures outliers in the distribution) and d50 (median): diameter of the particle that 50% of sample's mass is smaller than and 50% of sample's mass is larger than (Source: Bittelli *et al*., 2019).

7.5 Particle size analysis methodology conclusions

There is no straightforward relationship between sedimentation and laser diffraction methods. A significant difference between methods is that sedimentation methods measure mass percentage of particles (i.e. the amount of matter) and LD measures volume percentages (i.e. how much space is taken up) based on an optical diameter. Indeed, Loveland (2016) has argued that neither method is 'correct' due to inherent assumptions about particle sphericity and uniform density (sedimentation methods) or uniform optical properties (LDM). Loveland (2016) suggests that typically small soil particles (<10 µm) will be platy (rather than spherical) and inhomogeneous and so both methods are subject to different constraints. However, comparison with direct observation through digital imaging showed that LD was a closer representation of the true distribution than sedimentation based methods (Bittelli *et al*., 2019).

Laser diffraction has many advantages (short analysis time, high repeatability, low sample volume, a wide measurement range and a wide range of sorted fractions) and a variety of commercial instruments are available. However, correct use of the machinery and interpretation of results is essential. LD produces fine resolution data for the entire particle size distribution, and while it is possible to make intermediate measurements, most sedimentation particle size methodologies only measure the quantity of particles corresponding to a small number of categories, e.g. <0.002, <0.02, <0.2 mm, and >0.2 mm. Sedimentation methods are also relatively time consuming and rely, to some extent, on the laboratory operative to perform the analysis accurately and ensure correct sampling times and temperature regimes.

Errors made in sample preparation are often the largest part of the total error for the LDM and can be attributed to: non-representative sub-samples, inefficient dispersion, comminution (reduction in particle size) during dispersion, air bubbles (due to foaming dispersants or vigorous stirring) and scattering caused by changes in temperature.

For both LD and sedimentation methods it is essential that samples are properly dispersed. Chemical dispersion uses dispersing chemicals to break up soil aggregates into their primary constituents whereas physical dispersion uses ultrasound energy (sonication) to physically disrupt soil aggregates (Yang *et al*., 2009). Where a sample is not fully dispersed the number of clay sized particles will often be underestimated as they remain 'attached' to larger aggregates and may be incorrectly classified as more coarse (i.e. silt) particles.

All methodologies make assumptions about the spherical shape of the soil particles, which in reality will depend upon the characteristics of an individual soil sample. For example, platy shaped grains lead to fine fraction overestimation while disc or rod shape grains result in underestimation of the 0.0001 mm to 0.100 mm range (Di Stefano *et al*., 2010). However, it is difficult to estimate for which of the methods the error caused by the lack of sphericity is more significant. The heterogeneity of particle densities causes uncertainty in the results from both sedimentation and LD methods. Sochan *et al*. (2014) used light microscopy to measure the size of particles remaining after sedimentation compared with the theoretical size of remaining particles (based on Stokes Law). They noted that for each size fraction (e.g. <0.063 mm) particles which were larger than the upper limit were measured. This was attributed to the particle shape (plate-shaped) and density (i.e. particles that were less dense than the average for the soil sample). Sochan *et al*. (2014) noted a clear trend: the smaller the particles (i.e. greater the clay content), the higher the deviation from Stokes' law.

Other factors that can affect the PSA results obtained using the LD, include: the number of lasers and the choice of measurement time. There are also post-processing factors that can change the LDM PSD, such as the choice of Fraunhofer or Mie diffraction models or the optical parameters used (e.g. Ryżak and Bieganowski, 2011; Özer *et al*., 2010), however, these can, be changed and reapplied to the original measurement data.

Overall, the LDM is a quick and useful method to determine particle size, although comparison of data obtained using other methodologies is not straightforward. For that reason it is vital that the methodology used for PSD should be clearly stated so that any comparison between datasets can be fairly made. The ALC and preceding Soil Survey of England and Wales work was calibrated using the pipette method and as such care would needed in moving to the LDM.

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