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Research Review No. 95

Analysis of top and subsoil data from the High Speed 2 (HS2) rail project

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1. Executive summary

More than 1,400 data, collected as surveys along the High Speed 2 (HS2) routes from London to Crewe and Leeds, were analysed. Samples, topsoil and upper subsoil (to 50 cm), were measured at NRM Laboratories. The main trends identified will help inform revisions of the *AHDB Nutrient management guide (RB209)*.

Overall arable phosphorus (P) and potassium (K) levels showed more deficiency than routine Professional Agricultural Analysis Group (PAAG) surveys. This is, in part, because the latter data was sampled to 15 cm depth, compared to full depth of identifiable topsoil (22–35 cm) in the HS2 surveys. The discrepancy from PAAG was even more extreme on grassland, which was sampled to at least 20 cm in the HS2 samples.

Soil texture has a major influence on nutrient levels; P deceases from light-to-heavy texture, with the contrary trend for K and Mg. The persisting incidence of many low and high samples on arable and grassland indicates that RB209 uptake is limited and/or the RB209 method for equalising index using builds/run-downs needs modification according to soil type.

In many cases, upper subsoil P is about half topsoil P. However, when above 35 mg/l, the subsoil P can rise rapidly on lighter soils. Clay soils have proportionately less P in subsoil, but levels are variable, probably linked to the degrees of organic matter carry-down into subsoil. A guide limit of 35 mg P/l in topsoil is suggested for applying P fertiliser, *whenever subsoil has underdrains, groundwater or is sandy/sandstone*. P in the upper subsoil declines with depth and risk of transmission in heavy soils is best gauged by measuring P *below* 40 cm depth.

For the same topsoil K, subsoil K is lower in sand, light loamy or stony subsoils, compared to medium or clay subsoils. Subsoil K is not wholly predictable from texture and topsoil K, though usually is >90 mg/l when topsoil is >150 mg/l. Potassium response trials need to measure subsoil K. Revision of target to the upper part of index 2- (150–180 mg K/l) should guarantee supply from subsoil, if the topsoil dries out. Clay subsoils were rarely lower than 90 mg K/l, except Carboniferous clays, which are poor K status, compared to Triassic (red) or Southern (younger) clays. A table is proposed to categorise which clays are high K-releasing, non-releasing and intermediate.

Magnesium (Mg) is higher on clay soils and ultra-high Mg (index 6, 7) was found in some Midlands and Carboniferous formations – on these, low K:Mg ratio was common. A provisional recommendation is that K target index should be raised to 2+ on ultra-high Mg soils. Low Mg occurred mainly in the Southern region and on lighter or stony soils, where the subsoil Mg was lower than topsoil, contrary to the trend on medium and heavy subsoils.

Subsoil pH usually exceeded topsoil pH on arable and grassland, though it could be close to parity on some extensive grassland and woodland. Measurement of subsoil pH is recommended on clays when pH is below 5.5, lighter soils below 5.8 and all soils below 6.0 and not limed within five years. A calculation is given for lime requirement of subsoil.

Organic matter (OM) shows a limited increase with clay content, from 3% on light to 4.5% on heavier soils. Realistic targets are given for arable farmers. Loss on ignition methods are unsuitable and there is a need to standardise depth protocols for measuring OM in topsoil and in subsoil. Corer/gouge auger is preferable to Dutch auger.

Grassland and woodland have significantly higher OM than arable land in the topsoil. Tentative values are cited for carbon stocks to 50 cm depth.

C:N ratio is typically 10–11:1 but varies from 8–14:1, decreasing with clay content and increasing with carbon content. Total nitrogen is best measured directly, rather than inferred from carbon measurement.

2. Background

The upper subsoil in soil, defined as the horizon beneath topsoil to about 50cm depth, is an important source of nutrients to crops, especially nitrogen and potassium. Its structure and nutritional status, especially phosphorus, can influence the speed at which roots develop, tapping water and nitrogen from far deeper in the profile.

In UK there is a scarcity of information on subsoil nutrients apart from occasional trials [1].

Along the proposed High Speed 2 route from London to Crewe and Leeds, HS2 Ltd required soil surveys to inform its Environmental Impact Assessment of the scheme, and to assist in restoring affected land to its original condition once the project was completed. This involved many taking samples of topsoil and upper subsoil for nutrient analysis over a large range of geological formations and associations in the national soil map.

HS2 Ltd kindly gave permission to use the data with the proviso that the exact point locations were not disclosed.

Most soil surveys were conducted by five qualified staff of Reading Agricultural Consultants, and one of them, also a FACTS trainer and fertiliser agronomist, approached AHDB for knowledge exchange funding to analyse the data the relationships between soil nutrients, pH, organic matter, and texture, and between levels in upper subsoil and topsoil.

AHDB contributed £2,700 towards the data compilation and analysis.

1 e.g. I.R. Richards et al. (1998) *Journal of Agricultural Science*, *Cambridge* **131**, 87-195.
Also, Rothamstead have measured subsoil nutrients in their trials.

3. Introduction to the data set

The data was analysed in three main regions as shown on the map. WP1 (East Midlands to South Yorkshire) comprises soils formed Carboniferous Mudstones and Siltstones interspersed with Sandstones. WP2 (Leamington to Crewe and Nottingham) is soils formed on reddish Triassic Mudstones, Siltstones and Sandstones, locally covered by Glacial deposits (of similar colour). WP1 and WP2 comprise a range of textures from sandy to heavy loam. WP3 (London to Leamington) is data is chiefly heavier soils formed on a succession of geological clays – Lias to London Clay – locally capped by Glacial deposits, Clay-with-Flints or Gravels – plus occasional exposures of limestone.

WP 1 : East Midlands to South Yorkshire	(225 data)
WP 2 : Leamington to Crewe and Nottingham	(800 data)
WP 3 : London to Leamington	(409 data)

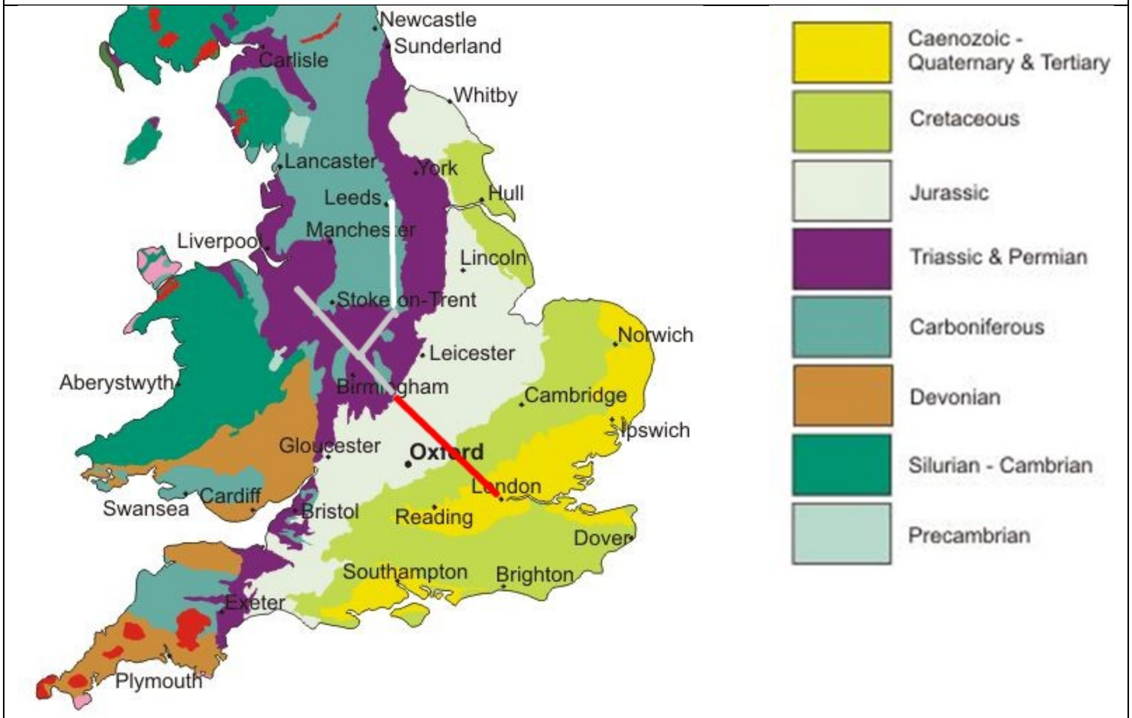

Figure 1. Map of survey transepts

Sample grid

Nutrient samples were taken about one per 3 hectares or in clusters of up to 5 per ha. The former was used in WP1 and most of WP3. WP2 contained equal representations of wide and close space samples so for purpose of giving more representative regional averages, two out of three cluster points were excluded (at random). All data were used for examining relationships between topsoil and subsoil nutrients.

Sampling procedure

Soil samples were composites of 5 cores within 10 metres of the survey point, taken by one of two methods:

a) topsoil to standard depth (0-20/22cm) by a 1.8cm-wide hand corer, followed by subsoil sample from 25cm or 30cm to 50cm by a 1.2cm diameter gouge auger,

b) Dutch auger sample of topsoil and main upper subsoil horizon (start depth 25 to 35cm).

Some methodological differences emerged, with the corer tending to somewhat higher levels of Organic Matter and phosphorus than the auger, linked to shallower start depth of subsoil and the inclusion of the surface layer on grassland. This is fully discussed in WP 2.3 and does not invalidate the overall findings in the reports, but has implications for future testing (see discussion).

Clusters of 3-5 samples taken by corer were used to assess short-range variation of nutrient levels within a hectare area.

Short range variation for P, K and Mg in arable land was typically ±15% provided there was no texture variation. Organic matter was ±11% and pH ±0.2. P variation increased to ±25% on grassland and ±65% in woodland. See WP3-18.

Texture

Each horizon was hand textured by experienced surveyors, and using the standard MAFF (1998) Land Classification protocol [3] with the middle categories split, upper and lower +/- 26% clay.

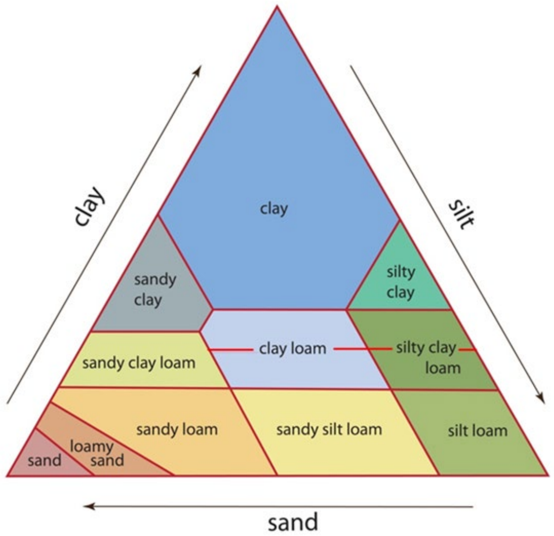

Figure 2. Texture diagram (UK system)

For statistical purposes hand-textures were grouped according to estimated clay content
Sands : very light soils, sand or loamy sand, <10% clay.
Light loams: sandy loam or sandy silt loam, 11-17% clay.
Medium loams/silts : sandy clay loams, clay loam or silty clay loam, 18-26% clay.
Heavy loams/silts: sandy clay, clay loam or silty clay loam, 27-35% clay
Clays: silty clay or clay, >35% clay.

Where the upper subsoil comprised two textures, the average clay content was ascribed, e.g. medium loam over clay was placed in "heavy loam" category.

Stoniness was grouped into five categories, <5%, 5-14%, 15-24%, 25-40% and > 40% by volume. Stone is any particle >2mm and estimates are subject to greater error than hand-texturing, especially in subsoil.

Nutrient Analysis

Samples were taken over the period 2016-20 and all analysed at NRM Laboratory for pH (in water), P (Olsen), K and Mg (M ammonium nitrate) and Organic Carbon by Dumas method after removal of carbonates. The cluster samples were analysed for Total Nitrogen (Dumas).

Analysis values in mg/l are used in the statistical analysis. Sometimes they are grouped into index ranges as in AHDB's Nutrient Management Guide RB209 [5] (see WP3-2, WP2-3).

Organic Matter (SOM)

Organic Matter was derived multiplying organic Carbon by 1.72. This was rated in two ways a) the SSEW system [2] dividing in 1.5% segments and b) the new approach based on Clay:Carbon ratio [5]. The method by which data is processed is in WP3-Tables 2.2 and 2.3.

Geology and Soil Type

Each data point was pinpointed to a British Geological classification [1] and soil association. Each datum was ascribed Geological type, 'Solid' and 'Drift' (if present) and the Soil Association from the 1:250 000 national maps [2].

Land Use

In most cases this was noted by the surveying teams, and ascribed a value 0-4 for arable, ley, extensive grass, amenity grass and woodland respectively.

1 http://mapapps.bgs.ac.uk/geologyofbritain/home.html

2 Soil Survey of England and Wales Bulletins 10, 12 and 15 and maps.

3 MAFF (1988) Agricultural Land Classification of England and Wales

4 Prout JM, Shepherd KD, McGrath SP, Kirk GJD, Haefele SM. (2020) What is a good level of soil organic matter? An index based on organic carbon to clay ratio. European Journal of Soil Science 1-11.

5 AHDB (2017) Nutrient Management Guide RB209.

4. Aims (RB209 improvement)

The project explored possible RB209 modifications by the following questions:

1) When should the upper subsoil be tested for P K, pH?

2) When might subsoil need liming?

3) Is subsoil sampling necessary in future AHDB-RB209 research trials?

4) What is the extent of English soils deficient in P or K?

5) When is topsoil P at target (index 2) insufficient because of poor subsoil P?

6) What are P maxima to prevent excessive subsoil P and transmission to groundwater?

7) Where might K index 2- not guarantee sufficient supply to crops because of poor subsoil supply?

8) Should soil K recommendations be modified according to soil texture and mineralogy?

9) Likely extent of K deficiency induced by high soil magnesium.

10) In RB209 (SNS) is it valid to use organic matter as a surrogate for total N?

11) Improve the data bank of SOM levels in topsoil and upper subsoil. What levels should farmers reasonably aim for?

5. Phosphorus

Variable soil P

Topsoil phosphorus values were highly variable. In Arable land 48%, 23% and 40% were at index 1 or 0 in the three regions WP1, WP2 and WP3, respectively. This was somewhat higher than PAAG (2019-20). 25%, 42% and 29% were index 3 or higher.

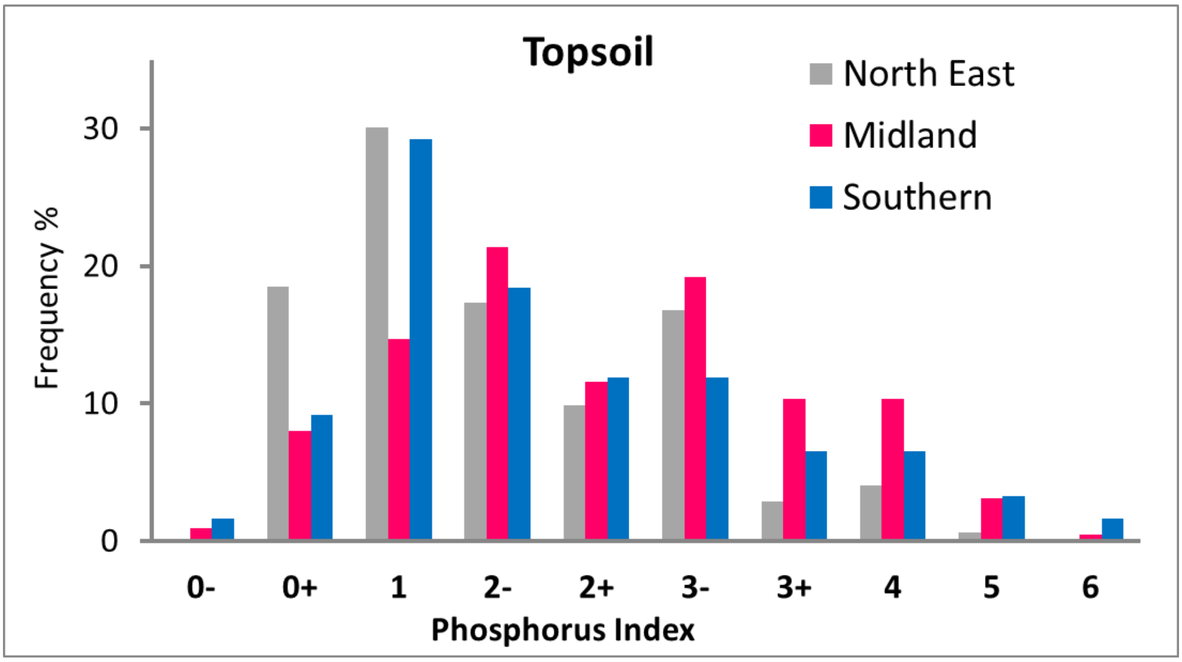

Figure 3. Regional comparisons – phosphorus in arable topsoils

Table 1. Extent of phosphorus deficiency (topsoils)

At soil Index 1 or 0		**P**	**P**	**K**	**K**
Region	**Geology**	**Arable**	**Grassland**	**Arable**	**Grassland**
East Midlands to Leeds	Carboniferous	48%	75%	47%	77%
Central and NW Midlands	Triassic (red)	24%	56%	41%	66%
Leamington to London	various	40%	51%	20%	32%
PAAG (2019/20)	all	23%	34%	25%	42%

A very high % of grass was deficient, especially extensive grassland (WP-2.4). The difference to PAAG is partly due to sampling at 20cm+ instead of the (0-7.5cm or 0-15cm), but indicates that overall P fertility in the topsoil is not good.

Soil texture is important

Topsoil texture was partly responsible for the variability in P levels, with an overall decline as estimated clay content increased.

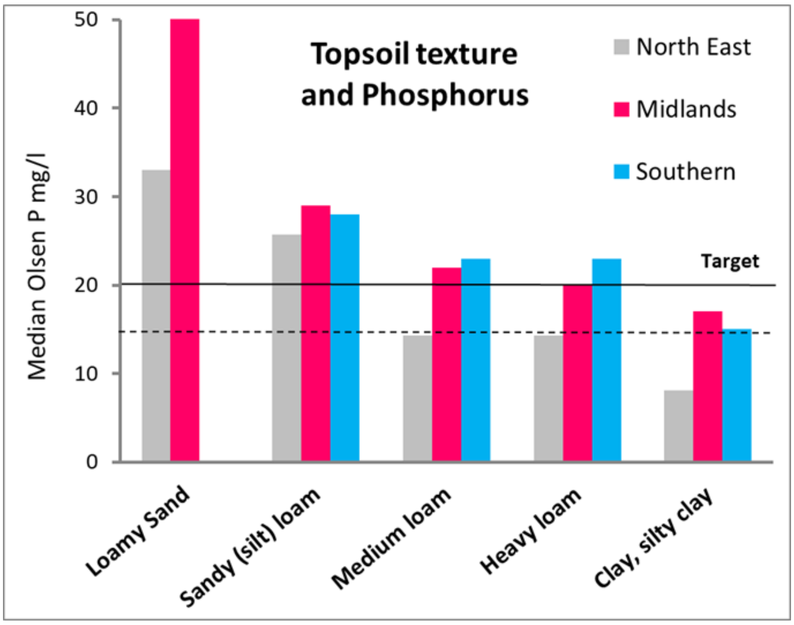

Figure 4. Arable median values of topsoil phosphorus according to soil texture

Although clay topsoils tended to low P index, there were many exceptions to this rule. Across all textures P levels are lower in the North East, either due to mineralogical differences, or local management factors e.g. shortage of animal manure in this predominantly arable area. Some lighter soils had low P, notably on iron-rich deposits (WP3-4).

Typically, in heavy topsoils an increase of 1% Soil Organic Matter was associated with a 2 mg/l rise in topsoil P (WP3-Appendix AG).

In the Midlands data, soil redness had weak effect on soil P which was lower only in *very* red horizons (2.5YR hue), WP2-Table 8.

Phosphorus in upper subsoil

Table 2. Median P and K levels in subsoil

Subsoil P,K mg/l		**P**	**P**	**K**	**K**
Region	**Geology**	**Arable**	**Grassland**	**Arable**	**Grassland**
East Midlands to Leeds	Carboniferous	7	5	85	68
Central and NW Midlands	Triassic (red)	12	7	101	71
Leamington to London	various	7	6	132	127

In the NE 60% of arable subsoils were index 0 and 36% in the Midlands. Under extensive grassland >60% of subsoils were ≤5 mg/l P and some below 2.5 mg/l.

However there was a big range in subsoil P. Approximately, 40-70% of the variation was accounted for by topsoil P. Light and medium subsoils tended to be one index lower than topsoil, however above 35 mg/l the subsoil P could climb quite rapidly, especially in lighter soils, suggesting high downwards transmission (WP1-Figure 3a, reproduced below, also found on a larger data set in WP2-Figure 8ab).

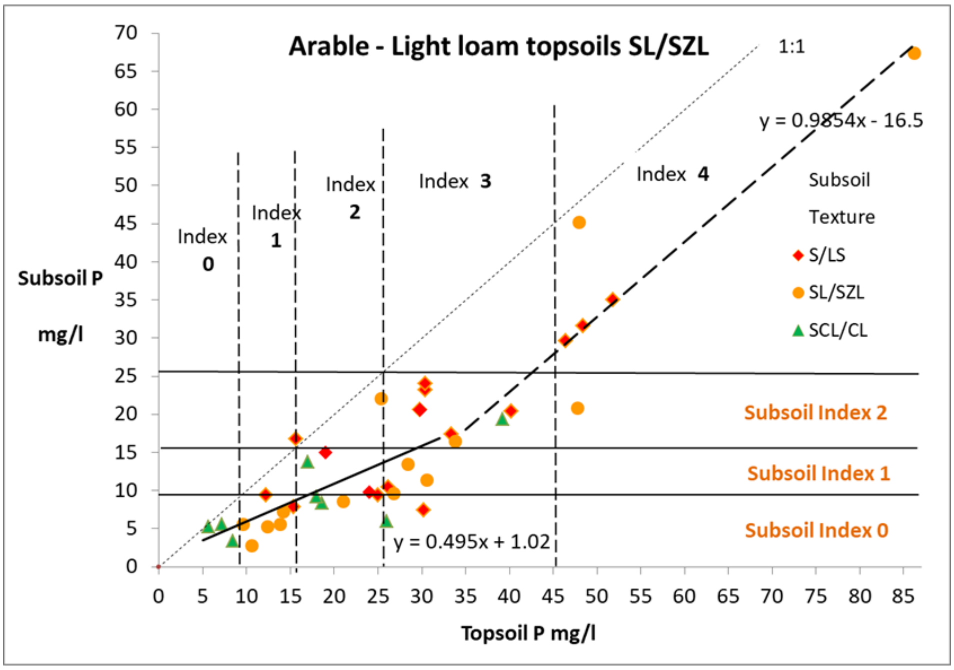

Figure 5. North East region, arable samples, phosphorus in topsoil and subsoil

In heavier subsoils, subsoil P was less responsive to increases in topsoil P. Clay subsoils remained in index 0 when topsoil was index 2 (or lower index 3 on many Southern clays). See WP1-Figure 3c, WP2-Figure 8a and WP3-Figures 7.1/10.1/10.2/11.1 and 6.1 reproduced below.

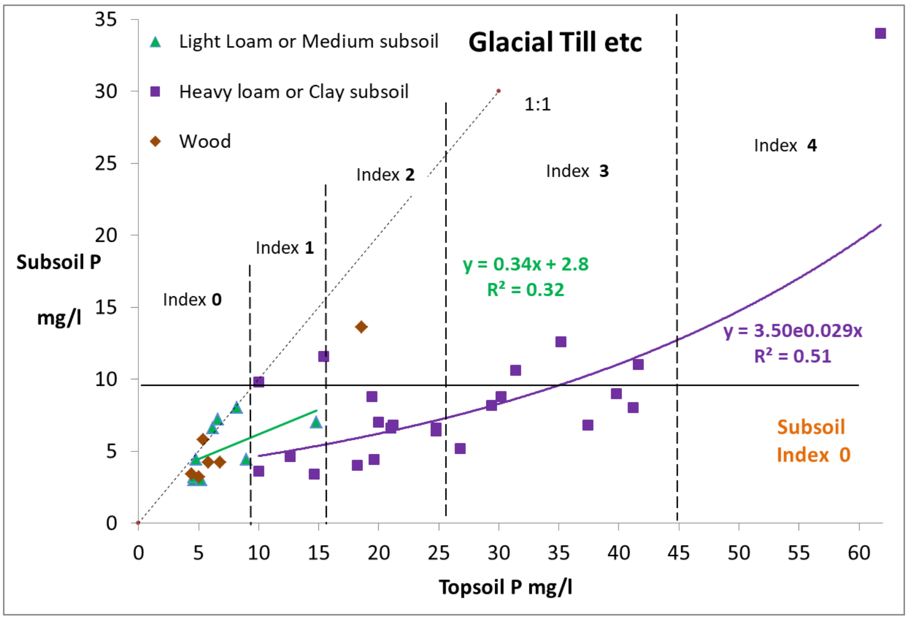

Figure 6. Glacial soils (Southern arable and grass). Phosphorus in topsoil and subsoil.

Even accounting for subsoil texture, only half the variation in subsoil P was explained by topsoil P. One factor was start depth of subsoil sample, with corer method averaging 1 mg/l P higher than auger samples under arable and 3 mg/l under grass (WP2-Table 5).

Each 1% increase subsoil OM up to 6% was associated with a 1 mg/l increase in subsoil P (WP1-4.2, WP2-4.4,WP3-Tables 3.3,10.3), higher in some clay groups (WP3-Table 7.3).

Much variation could be management-related. It seems the available P in subsoil is linked *to carry down of organic matter* by rooting, earthworms or deeper cultivation, all of which are likely to be more restricted in clays. Almost certainly P decreases over the soil depth 25 to 50cm in most cases.

6. Potassium

Variable Potassium levels

As shown in table 1 in the three regions 47%, 41% and 20% of arable topsoils were index 1 or 0, more than PAAG (2019-20), 25% in WP1, WP2 and WP3, respectively. High K, index 3 or 4, was rare except in the Southern part (30%) although all regions had significant numbers at index 2+ which constitutes some surplus of soil K.

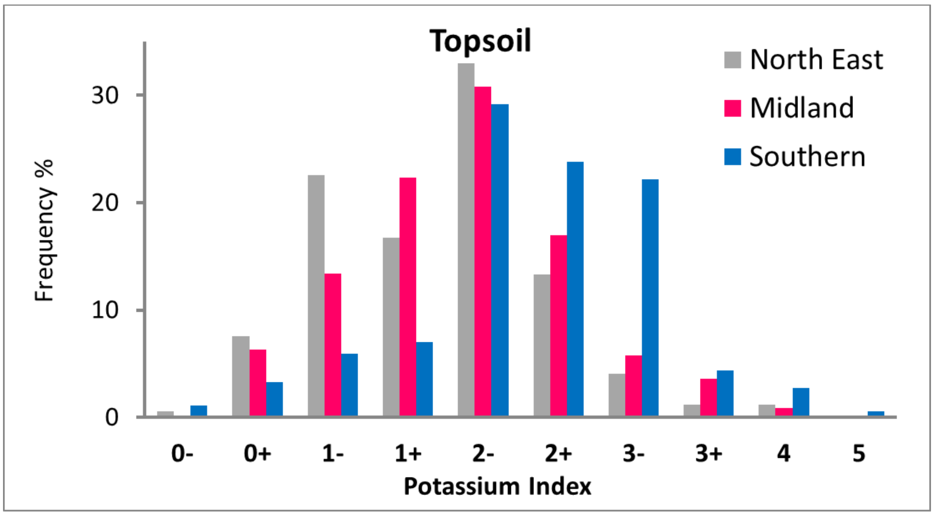

Figure 7. Regional comparisons – potassium in arable topsoils

K levels under grassland levels were lower than arable in all regions; 64% of the grass leys in the Midlands were deficient (WP2-Table 6). This relates to 20cm+ sample depth.

Topsoil K correlated with topsoil P suggesting a strong management influence (WP1-5.2, WP2-5.2).

Topsoil K is affected by soil texture

Potassium levels in topsoil increased sharply with topsoil clay content in the South (WP-17) and, to a lesser extent, Midland soils, but in the North East the trend was opposite, K being slightly less on heavier than lighter soils. This affirms that Carboniferous clay has very poor potassium supply.

Topsoil K was less if sampled in summer compared to winter (WP1-5.4) and a 25 mg/l increase was associated with 1 unit pH rise (WP1-5.2, WP2-5.2, some clays in WP3) and with a ~10% increase in stoniness in North East (WP1-5.4), presumably a concentration effect.

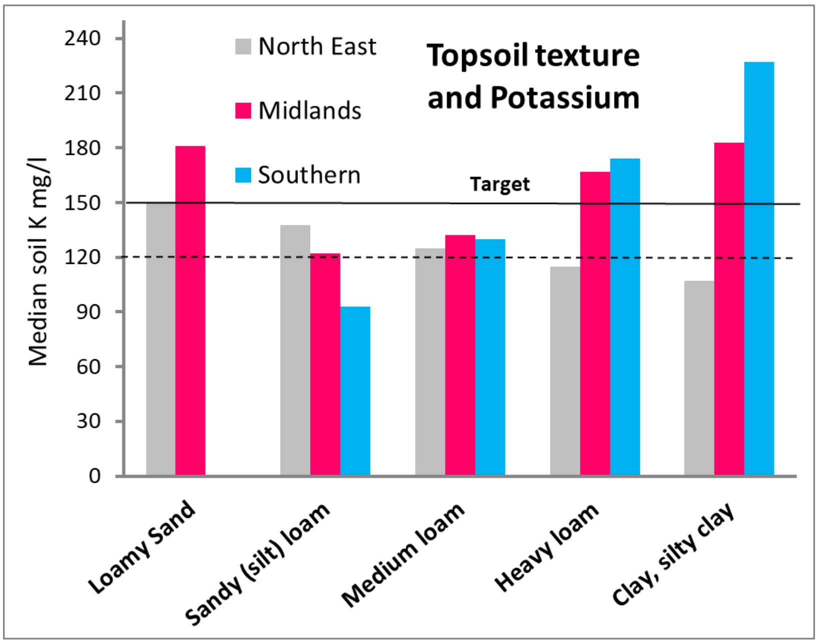

Figure 8. Arable median values of topsoil potassium according to soil texture

Potassium in upper subsoil

Median was index 1 except in the southern region (2-), see table 2. There was large influence of texture (WP3-13.4) though in the NE, heavy subsoils could be lower K than sandy ones (WP1-5).

Cereals may obtain up to 30% of their potash from the subsoil, especially in drier seasons. Some is returned to topsoil as the crop ripens, then over winter some topsoil K may leach into subsoil.

Accordingly topsoil and subsoil K are likely to be related though the subsoil K usually is lower. The pattern is somewhat different on lighter, medium and heavier subsoils.

On light loam and sandy soils in the Midlands data, when the topsoil was index 2- the subsoil was most likely to be upper index 1 but was less than this in 38% of cases* (WP2-5.5). The trend line was 10 mg/l lower in grassland (WP2-Table 8).

In lighter and stony medium subsoils of the Southern data, the trend was for lower K than the Midlands data (see Figure 9).

Only 60% of the variation is accounted for by the idealised plots below Figure 5.3. Subsoil organic matter had no influence in some data sets but in others each Δ1% OM was associated with a 10 mg/l increase in K (WP1-5.2,WP2-5.4,WP3-3.3,7.3, 9.2) .

Subsoil stoniness had a small positive effect in some cases (WP3-9 & Table 5.2). At high topsoil index (3) the K in sandy or light loam subsoils climbed in some cases while not in others (a wide range of 100-200 mg/l, WP2-Figure 11a).

* on mediums and heavy loams the likelihood was 21%.

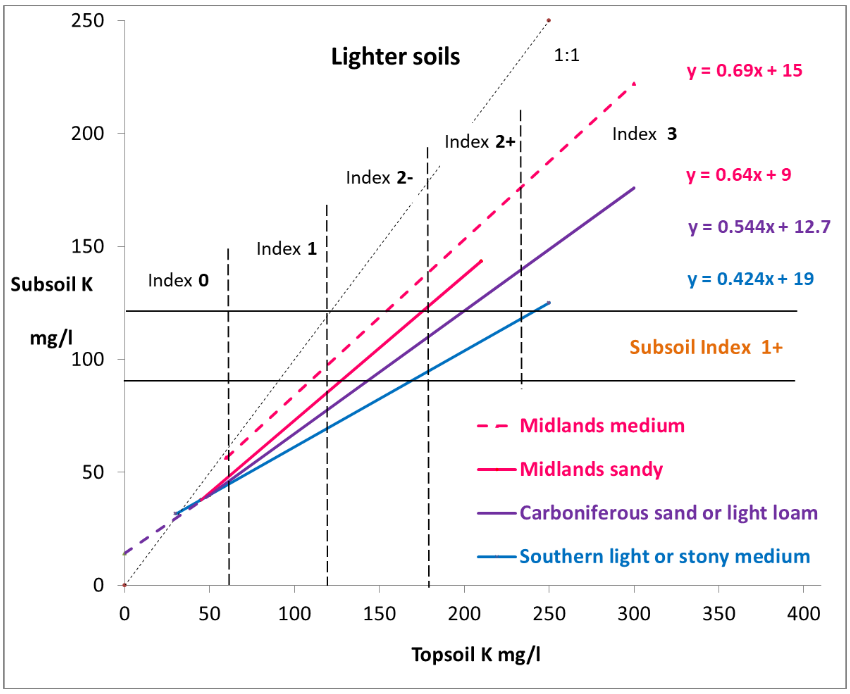

Figure 9. Generalised relationship of subsoil to topsoil K, light and medium soils.

On heavier soils, the subsoil K was lower on Carboniferous clays where <60 mg/l (index 0) could be found in topsoil and subsoil. Subsoil K was higher in Southern and Midland (red) clays; topsoil and subsoil converge at 90 mg/l, and it was rare to find any heavy arable soils lower than this.

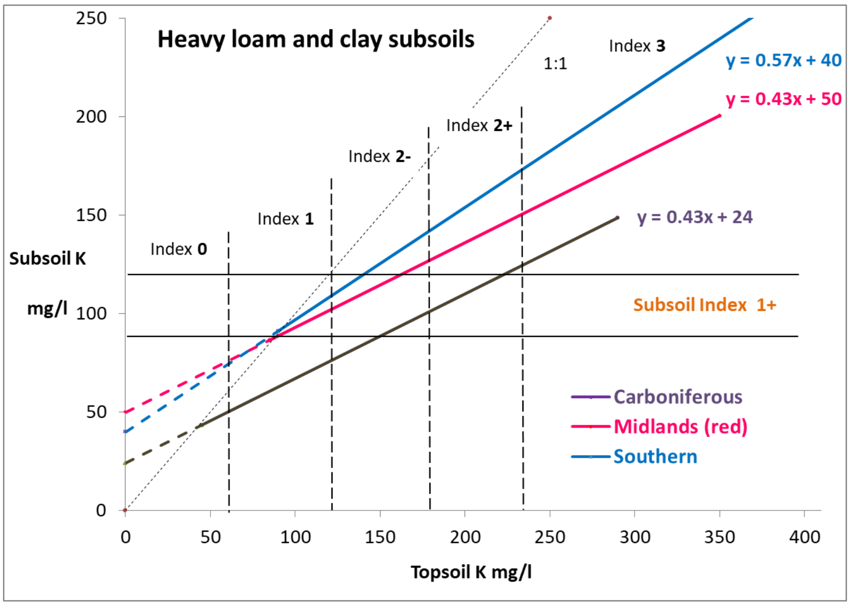

Figure 10. Generalised relationship of subsoil to topsoil K, heavier subsoils.

There are differences in potassium-supplying capacity between clay types lumped together as Southern in the graph. Clays that have retained their natural lime had better potassium status than similar clays that have lost it (decalcified) and depth of decalcification could vary even within the same field. In two of the Southern clays *topsoil K* increased 90 and 45 mg/l with a one unit increase in *subsoil* pH (WP3-Figures 7.3 and 6.5, below).

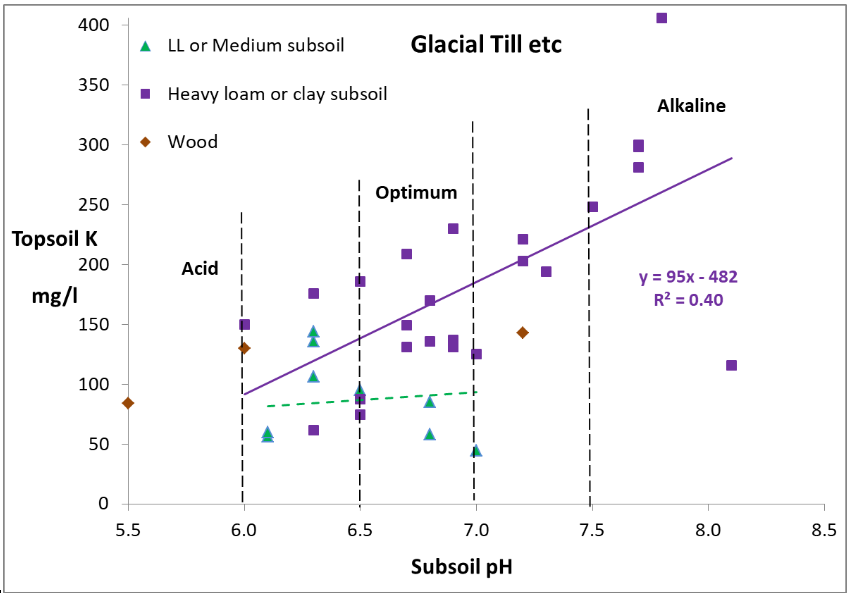

Figure 11. Glacial soils (Southern data arable and grass). Topsoil K related to subsoil pH.

On heavy soils, the intercept of 40-50 mg/l subsoil K at projected zero topsoil K raises some issues of whether this is actually plant available.

7. Magnesium

Variable soil Mg

Topsoil magnesium values spanned a large range. Only 6% of arable land was index 0 or 1 in the NE, 6% in the Midlands but 17% in the Southern region (PAAG 15%). The South showed most variation including 27% at index 5 or higher. A similar proportion of samples were very high in the NE. Midlands was least 13%, but still above the PAAG (2019) value of 12% for the whole of England.

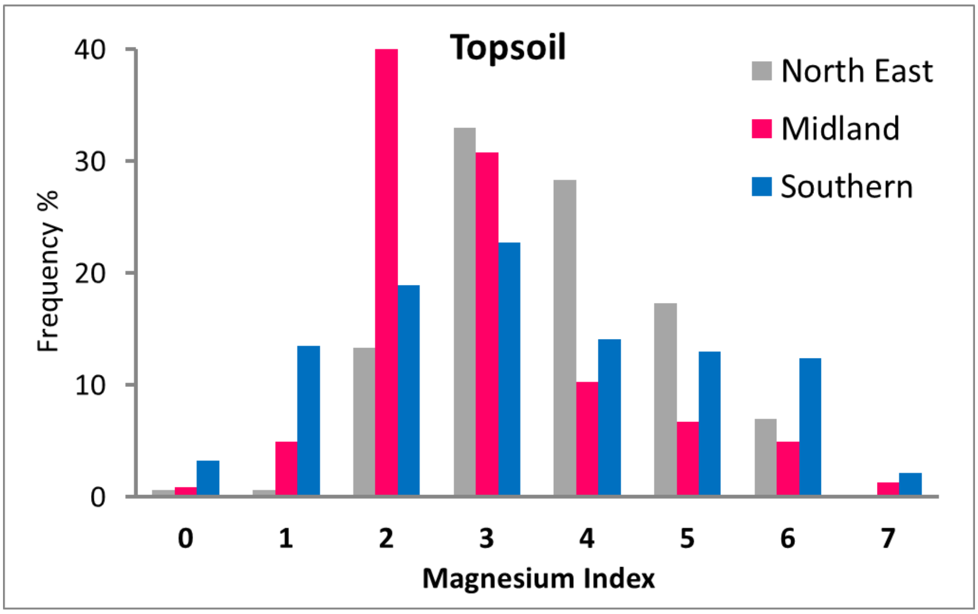

Figure 12. Regional comparisons – magnesium in arable topsoils

Mg higher in grassland

Grassland levels were higher in all regions. Leys were only slightly higher than arable. The highest levels were in extensive grass and woodland WP2-Figure15a and Table 10. In the NE the grassland averaged 262 mg/l (index 5).

In grassland there are Mg returns in manures and grazing animals (fed supplements) as well as little offtake from uncut (extensive) grassland. PAAG 2019-20 found only 3% of grass at index 0 or 1, a value exceeded considerably by the Southern data (10%, WP3-14).

Soil texture has a large influence on soil Mg

Mg levels increase with clay content and are less on lighter soils because of a) lower clay content and CEC with greater susceptibility to leaching, especially when raised by large Mg additions, b) most clay minerals 'release' magnesium.

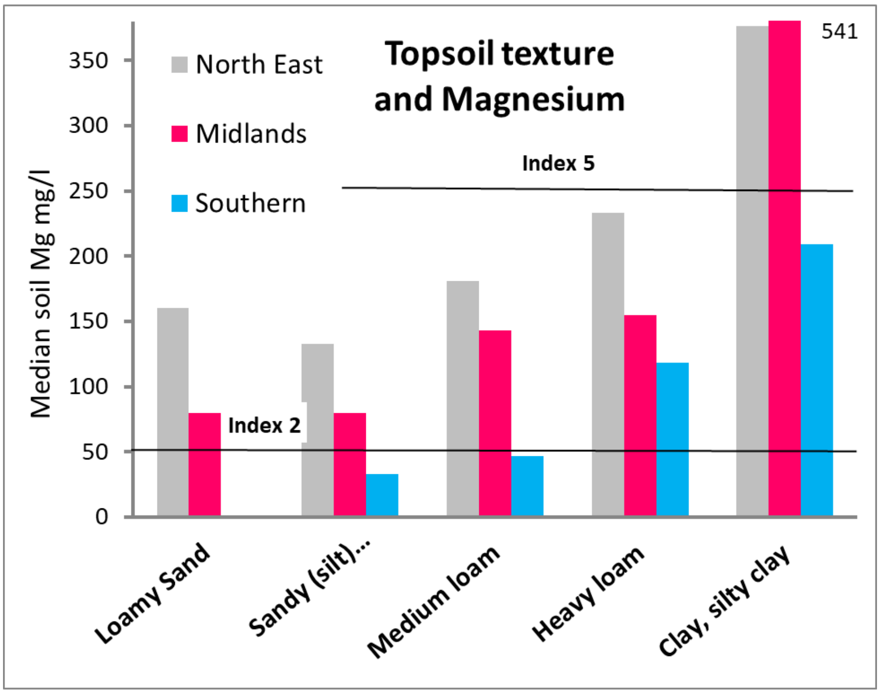

Figure 13. Arable median values of topsoil magnesium according to soil texture

Subsoil magnesium

Magnesium levels in subsoil spanned index 0 to 8 (WP2-Figure 15b) and were much higher in clay-textured subsoils (WP3-14.4).

The ratio of subsoil : topsoil Mg depended on the relative clay contents of both horizons (WP2-Figure 16a and b). As a rule "if the subsoil is heavy it has higher Mg than topsoil by 1.2-1.4 times, if medium textured is about parity and in sandy or stony soils is 65-80% of the topsoil Mg". A matrix is given in WP2-Table 14.4.

Low Mg in topsoil *and* subsoil was most acute in the Southern lighter or medium soils on stony Glacial deposits or Plateau Sand-&-Gravel soils. Clay-with-Flints topsoils were typically topsoil index 1 even where medium textured, and subsoil Index 0 (<26 mg/l).

High magnesium soils

Geology (mineralogy) and lime source are the key factors. A ranking is given below (see also WP3-Table 2.6).

In Carboniferous soils high Mg may be due in part to proximity to Dolostone (Magnesian lime) quarries in Notts and S Yorkshire, with heavy historical additions. Some Midlands areas also are serviced by Mg-containing limestones. The southern Jurassic limestones are much lower in Mg and Chalk contains almost no Mg.

A minority of the Carboniferous and Triassic mudstones/siltstones have residual dolomitic material in them resulting in very high Mg index (6-7) but pH is not a good predictor of high Mg which seems to attributable largely to clay mineralogy.

Geological Grouping	Topsoil Mg mg/l	Subsoil Mg mg/l	Subsoil K mg/l	Subsoil K:Mg
Dolomitic Siltstone and Dolostone	450	550	125	0.25
Alluvium on Triassic Mudstones	450	525	75	0.15
London Clay *	255	485	130	0.30
Carboniferous Mudstone/ Siltstone	225	275	70	0.25
Triassic Mudstones & siltstones	250	275	110	0.40
Charmouth Mudstone (Lias)	280	325	155	0.50
Oxford & Kimmeridge Clays	230	260	180	0.70
Glacial Till on Triassic Mudstone	155	215	110	0.50
Glacial Till on Triassic Sandstone	125	130	75	0.55
Rhaetic Clay & limestones	135	165	200	1.2
Glacial Till (Southern)	110	95	105	1.1
Whitby Mudstone (Lias)	85	80	85	1.1
Jurassic clay & limestone	95	70	200	2.9
Clay-with-Flints	55	60	105	1.8

Table 3. Typical magnesium and topsoil levels in heavy subsoils index 5 >250 mg/l, index 1 <50 mg/l. * mainly grass so high Mg needs verification on arable soils.

Potassium deficiency induced by high magnesium levels

Generally 0.5:1 mg/l K: mg/l Mg is a guide maximum (Mg 2x K) though the source is difficult to locate. PAAG found 9% of all samples had ratio < 0.5. The data here shows it to be the norm for many subsoil clays.

Low K:Mg ratio in subsoil translates into low ratio in topsoil. In the NE at topsoil K index 1 ratio was usually less than 0.5 as it was for a significant number at K index 2- (WP1-Figure 1.13). Low ratio was also found in the Midlands though only where Mg index was 5 or more and was unlikely at K index 2+ (WP2-Figure 19, reproduced below).

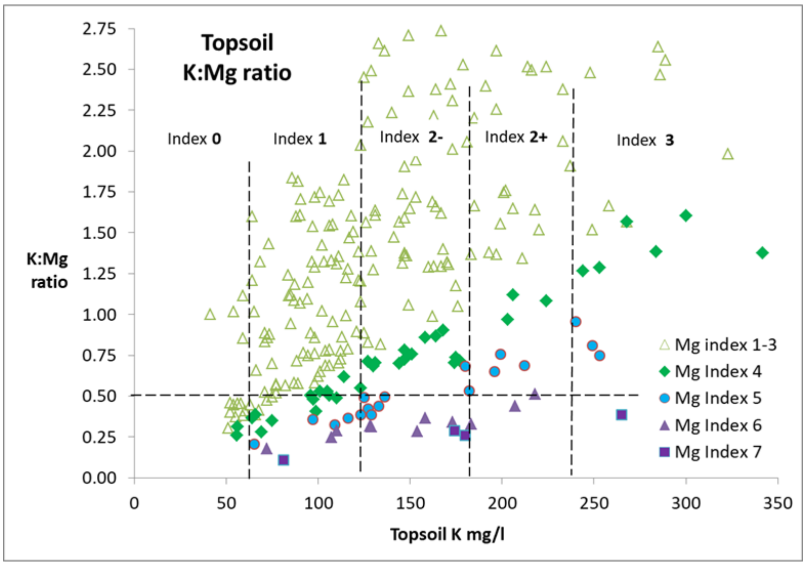

Figure 14. Potassium and magnesium in arable topsoils of the Midlands

Soil structural instability due to high magnesium is only likely at Mg index 6 on medium soils or 7 on clay-textured soils or Mg/CEC > 17.4 (see WP3-Table 14.4).

On high Mg soils, short-range variation is typically ±20%.

8. pH

On arable land the overall trends on pH are in broad agreement with PAAG 2019/20 with about 22% of samples suboptimal pH and 15% pH below 6.0.

Overall in grasslands pH is higher than reported by PAAG with fewer samples below pH 6 and fewer below pH 5.5. It is likely that a sample taken to only 7.5cm or 15cm depth would be more acid than when taken to 20cm+ depth as here.

Table 4. Proportion of acid and alkaline soils

Arable data	**median**	**< pH 6**	**6-6.4**	**> 7.4**
North East	6.9	6%	20%	17%
Central Midland	6.6	12%	28%	6%
Southern	6.7	17%	22%	21%
PAAG (2019)	6.8	15%	22%	24%
Grassland	**median**	**≤ pH 5.5**	**5.6-5.9**	**> 7.4**
North East	6.4	13%	8%	6%
Central Midland *	6.4 / 6.1	7 / 6%	14 / 32%	3 / 2%
Southern	6.7	9%	18%	19%
PAAG (2019)	6.0	16%	34%	3%

* leys and extensive grassland respectively

In the Midlands median pH was 6.6 arable, 6.4 leys, 6.1 extensive grass and 5.9 amenity and woodland (WP2-Table 14).

Alkaline topsoils were more common in the South than the other regions though a surprising number of Carboniferous arable topsoils were pH > 7.4.

Small effect of topsoil texture

In the Midlands the median was 6.4 for light loam soils, 6.5 medium and 6.6 heavy loams or clays (WP3-Table 15). There was a weak negative correlation with organic matter content.

In the South topsoil pH tended to be higher on heavier than lighter soils, though was more related to natural $CaCO_3$ reserve in subsoil rather than texture *per se*.

Subsoil pH is higher than topsoil

Subsoil pH was higher than topsoil pH in most cases. The average difference was 0.3 in NE (WP1-7) and Midlands (WP2-Table 14) and 0.5 in the South (WP3-Table 15.1).

The usual trend was convergence above pH 7.5 and widening difference so that below pH 6.0 subsoil pH was about 0.5 higher in heavy subsoils.

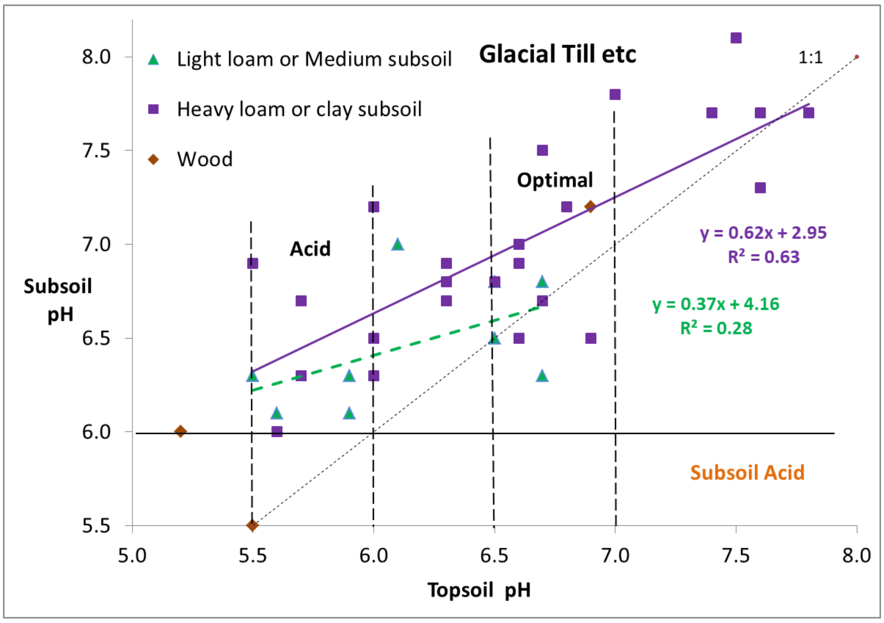

Figure 15. Glacial soils (South); pH in topsoil and subsoil

Influence of texture on subsoil pH

The Midlands data showed that the increase in subsoil pH compared to topsoil diminished with decreasing clay content (WP2-Figure 22a,b below).

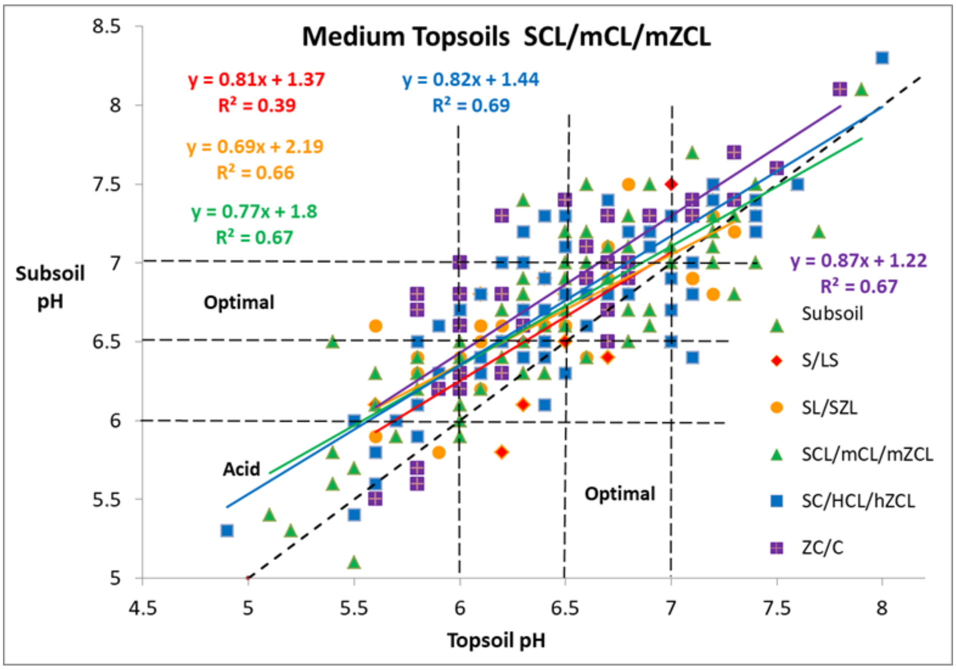

Figure 16. Midlands medium topsoils, topsoil pH, subsoil pH and subsoil texture

All the Midlands data was processed excluding topsoils of pH >7, and the best fits were found using topsoil rather than subsoil texture (WP2-7.4) as shown in Figure 17.

When topsoil pH is suboptimal (6-6.4), subsoil is expected to be optimal (>6.5) except on sandy soils. When topsoil is around pH 6.0, subsoil pH is typically 0.2 greater in sand, 0.3 in light loams, 0.4 in medium loams and 0.5-0.6 in heavier soils. When topsoil pH is below 6 subsoil pH is suboptimal but only likely to be below 6 when topsoil falls below 5.5 on heavy loams and clays or 5.8 on lighter soils. When topsoil is very acid (pH <5.5) subsoil is likely to be below 6.0 on any soil type.

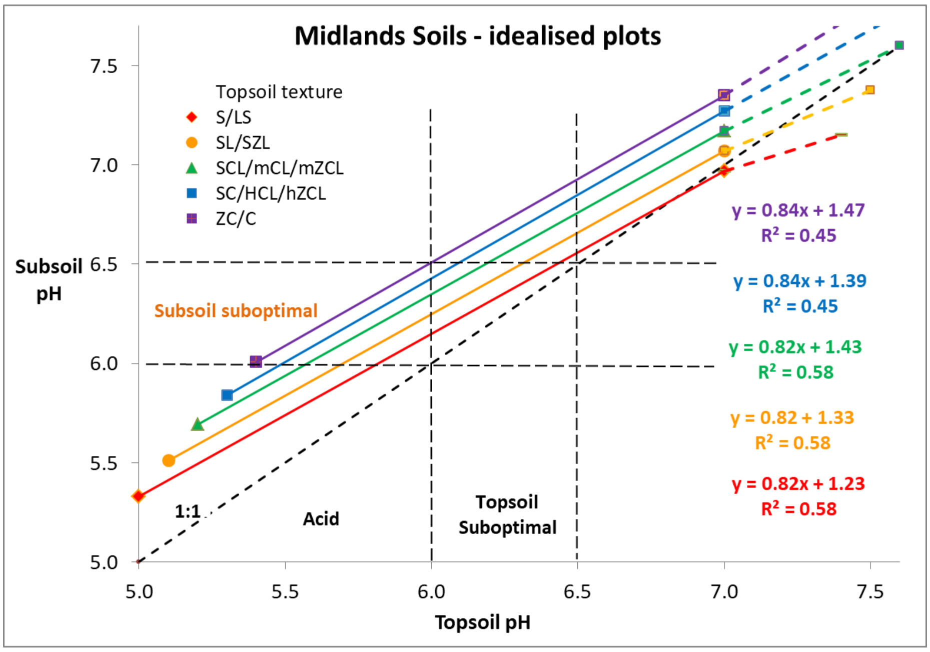

Figure 17. Generalised relationship of topsoil pH and texture and subsoil pH

In contrast, under woodland the topsoil and subsoil pH tended to be similar over the whole pH range 4 to 8 (WP3-Figure 15.2, WP2-Figure 23b), and in some very acid extensive grassland also the subsoil pH was similar to topsoil.

Unpredictability of subsoil pH

Above regressions only account for 60% of variation in subsoil pH. In a minority of cases the subsoil was *more* acid than topsoil.

Subsoil pH is expected to be higher than topsoil because of leaching, especially if lime has been recently applied. But with long neglect of lime, subsoil may decline to ≈ topsoil pH.

Topsoil pH risks being up to 0.3 units lower in summer if soluble salts accumulate - nitrate, sulphate and chloride - due to fertiliser application or mineralisation. It is likely that the subsoil is less susceptible to pH fluctuation but it was not possible to check from this data.

Subsoil OM% (capped at 6%) had a negative influence on subsoil pH with a decrease of 0.2 units between 1 and 4.5% OM, partly a reflection on more topsoil-derived material carried into the subsoil. When coal fragments or organic layers were present subsoil, pH could be 0.5 *lower* than topsoil, most common on disturbed profiles or layered alluvial soils (WP1-7.2).

Naturally alkaline soils

Topsoil and subsoil converge by pH 8 because of $CaCO_3$-CO_2 equilibrium.

In the North, alkaline subsoil (pH >7.4) occurred in a minority of Carboniferous clays, on dolomitic mudstones/siltstones with a few cases on Triassic mudstones (especially Worcester Association) and Glacial Till. Dolomitic (CaMg) carbonate was usually undetected by field HCl test.

The Southern clays were more likely to have alkaline subsoils, >70% of Oxfordian and Kimmeridge clays but only 25% of Glacial Till and Lias Clay subsoils (see WP3-Table 2.6). In cases of pH <7.8 residual $CaCO_3$ was usually present in too small amounts to be detected by field HCl test.

In Glacial Till chalk stones became evident in the clay at depths ranging from 25 to 80cm, indicating highly variable degree of decalcification (or variable chalk content in the original Till) resulting in alkaline and acid topsoils in the same field.

9. Organic matter

Loss On Ignition is an unsuitable method

On a comparison on 16 heavier samples, the LOI method showed a consistent increase of 2.6% Organic Matter compared to Dumas method, likely due to inclusion of structural water in the LOI meaurement (WP3-Figure 16.1).

Topsoil Organic Matter levels

In arable topsoils the median and modal range was 3 -4.4%, the medium category in Soil Survey manuals, somewhat higher in the South.

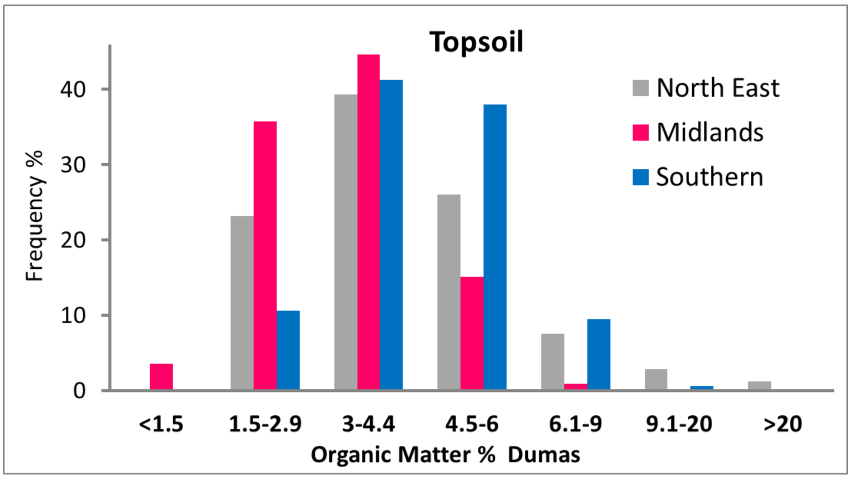

Figure 18. Regional comparisons – organic matter in arable topsoils

Table 5. Median organic matter levels in topsoil

	Arable	Leys Ext. Grass	Amenity	Woodland
North East	3.8 %	6.5 %	-	-
Central Midland	3.2 %	3.8 % 4.7 %	4.3%	5.2 %
Southern	4.5 %	6.4 %	5.7%	7.6 %

Grassland topsoils (to 20cm+ depth) typically had1-2% more OM than arable land, woodland somewhat higher. On grassland, the corer method tended to 0.4-0.7% OM higher than auger probably because it always includes the surface in the sample (see WP2-8.2).

There were few sites of OM > 10% (almost none in arable data).

Topsoil texture important but not preeminent

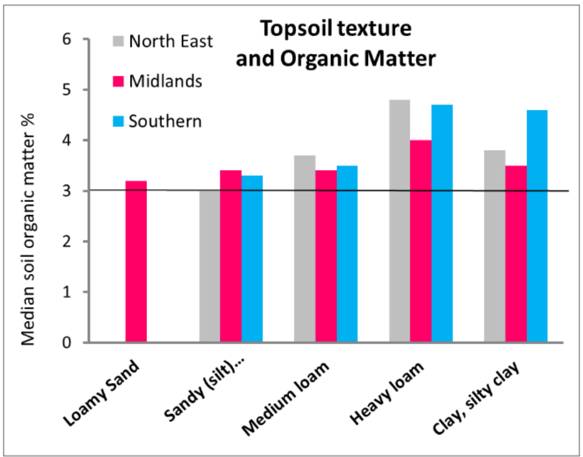

Figure 19. Arable median values of organic matter according to soil texture

In the Midlands median organic matter (arable/leys) increased from 3.2 on loamy sand topsoil to 4.4% on heavy loams (WP2-Table 19a). In the South 3.3% on sandy loams increased to 3.5% on medium loams and 4.7% on heavy loams and clays; grass was 3.9% in sandy loams and 6.5% in all other textures (WP3-Table 16.2). The lack of further increase heavy loam to clays (Figure 19) may be genuine, although confounded by the difficulty of hand-texturing heavy soils high in OM.

Texture influence seems limited to a 50% increase (∆1.5% OM) from light loams to clay soils though accompanied by a threefold increase in clay content (12-40%).

SOM index issues

The ratio of clay to SOC is seen as critical to soil quality with >13:1 considered as 'degraded', 10-13 as 'moderate quality', 8-10 as 'good quality' and <8 as 'very good structural condition'. This approach was applied to the Southern data in WP3-16. 65% of the arable land was classed "degraded", 13% of grassland and 19% of woodland (WP3-Table 16.6). In arable land 91% of clay topsoils were in the poorest class, 37% of medium/heavy loams, and 8% of light loams, while 54% of light loams were "very good" (WP3-Table 16.8).

Subsoil Organic Matter

This typically ranged 1.0 to 4.5%.

The NE (arable plus grass data) shows a 1.5 fold texture increase from 1.3% OM in sands to 2.0% medium-heavy soils (WP1-Table 10), the Midlands gave a smaller difference, 1.5 to 1.7% (WP2-Table 20) while in the Southern data it increased from 1.4 sandy loam to 2.3% clay subsoils (WP3-16.4).

In grassland, subsoil OM% was similar to arable land despite higher levels in the overlying topsoil. The exception was heavy wet soils under extensive grassland.

Relationship of subsoil OM to topsoil OM

WP2-Figure 25b, reproduced below, illustrates a wide scatter of data. Fits were improved by grouping according to subsoil texture. Clays (and possibly sands) fit to a lower sloping line (see also WP2-Figure 22a, WP1-Figure 21b). Southern soils gave diverse plots (WP3-4 to10) suggesting variable degrees of OM carry down in clay subsoils.

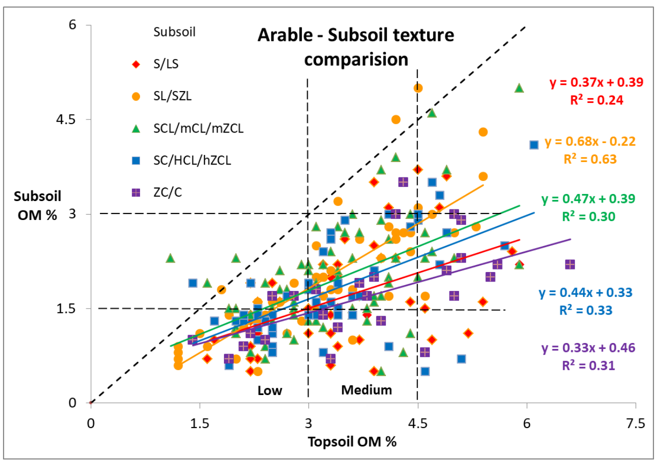

Figure 20. Midlands, Organic Matter in Topsoil and Subsoil and Subsoil Texture

Subsoil stoniness made no improvement in correlation except the Chiltern gravels (WP3-Figure 25b) which obviously had deeper OM penetration (every 10% increase in stones associated with a 0.18% increase in OM).

Prediction of subsoil OM

The generalised plot is based on equations fitted to the Midlands data (WP2-8.3) and Southern data (WP3-Table 16.5).

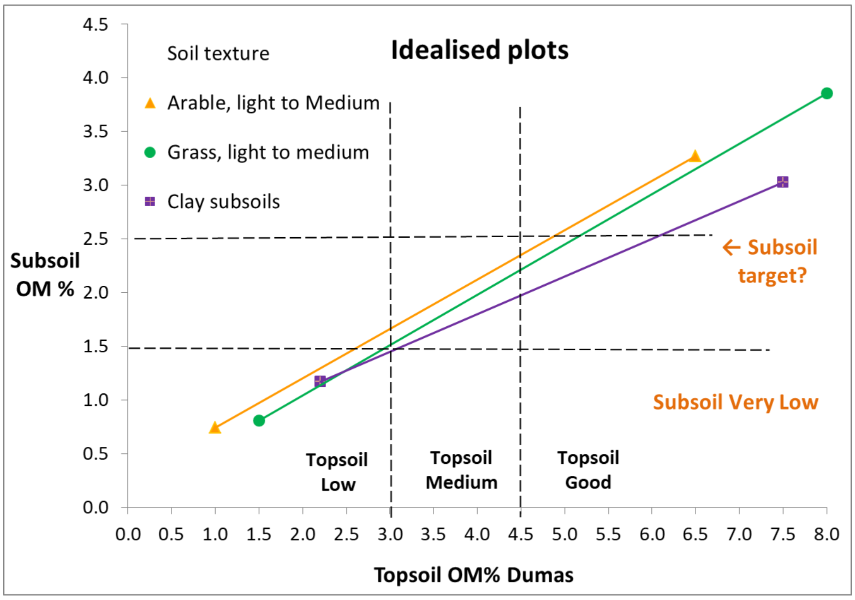

Figure 21.Generalised relationship of topsoil and subsoil organic matter

At 3% topsoil OM subsoil OM% is typically 1.5%, and increases almost in proportion to topsoil OM except in clay subsoils, where a 1.5% increase in topsoil OM is associated with only a 0.5% increase in subsoil.

However, with $r^2 < 0.40$, less than half the variation in subsoil OM was explained by topsoil OM and subsoil texture. Standard error of prediction was wide, ±0.65% OM. The corer typically gave subsoil OM 0.2% higher than lines on arable land and 0.13% in grassland, vice versa for auger. Start depth of subsoil sample tended to be less with corer (typically 25cm) than auger-surveyed points (typically 30cm) and this is significant because OM% decreases with depth over the 25cm to 50cm range.

OM penetration into subsoil is affected by historical deep cultivation and the amount of earthworm activity, both of which are inhibited on clay subsoils.

OM% could be higher in stony soils, because of deeper rooting or if stones concentrate the OM% input from roots, crop residues or soil amendments.

Predictability of subsoil OM was worst under high OM grassland or woodland.

2.5% OM seems a reasonable target to aim for in upper subsoil to optimise structure.

Carbon Calculation

Carbon stock depends on measured carbon value, stoniness and texture because bulk density decreases with clay content, 1.1-1.5 g/cm^3 clays to sands, though higher in compact (clay) subsoils. A calculation method has been developed and applied to this data but needs peer reviewing.

Provisional mean values are shown. In arable land more than a third is in the 25-50cm layer.

Table 6. Provisional estimates of mean carbon stocks to 50cm depth

Soil Carbon , t/ha	Arable	Grass	Woodland
North East	125	170	-
Central Midland	95	137	160
Southern	122	153	184

10. Total nitrogen

Data for south and Midlands regions is processed in WP3-17.

Total Nitrogen measurement is of environmental and agronomic relevance. It influences the release of available nitrogen to crops (and grass) by mineralisation. The AHDB winter wheat growth guide (2012) stated limits with organic matter measurement being used as a surrogate.

The average total N in Southern data was 0.3% on arable and amenity grass, 0.45% on grassland and woodland, higher than the Midlands data (0.19, 0.24, 0.21 and 0.28% respectively, WP2-Table 22). The difference was linked to higher soil organic matter in the Southern data which comprises mainly heavier soils.

Total Nitrogen was strongly correlated with organic matter (organic carbon x 1.72).
C:N ratio averaged 10.2 on arable and ley topsoils increasing to 10.8 on extensive grass and 12 in woodland; ratio was less in subsoil.

However C:N ratio could range 8-14:1 and tended to increase with increasing organic matter and decrease with increasing clay content. Arable, grass and woodland, topsoil and subsoil, all showed this trend (WP3-Figures 17.1-6).

Equations relating total N and C showed significant intercepts of 0.02 to 0.04% N at theoretical zero organic matter (WP3-Table 17.6). Texture adjusted equations ($r^2 > 0.8$) could predict TN from organic matter with a standard error of ±0.02 to 0.04 % N however some cases were very different. It is preferable to measure Total Nitrogen directly.

The author postulates some of the Total N reserve in non-exchangeable ammonium held in clay particles but most is in two types of organic N: held in clay-organic complexes and 'free' humus. The latter may have lower C:N ratio but higher mineralisation rate (see WP3-17 summary). This subject could be the basis of a research project to improve predictability of mineralisation N to crops.

11. Discussion and recommendations

Sampling depth for topsoil and subsoil

Most arable and ley profiles indicated an original cultivation depth of 25-35cm, which is substantially reduced in modern times. Thus there often is an intermediate horizon 20/30 to 30/35cm overlying the subsoil proper. Accordingly, it is important to standardise sampling depths, especially for phosphorus and organic matter assessment.

Suggested depths are 0-25cm and 25-50cm or 0-20cm, 20-40cm and 40-50/55cm.

The >40cm depth is important in under-drained heavy land to assess risk of P reaching the drains. On permanent grassland or minimal till land, the 0-25cm topsoil could be split 0-12 and 13-25cm.

Corer / gouge augers should be used, which include the surface.

Sampling method

There is short-range variation so it is imperative to take composites of at least 20 cores.

For monitoring changes in organic matter (after 5 years) this is best based on GPS-delimited areas whether a) small (~0.25 ha) plots or b) larger (1-4 ha) zones, in both cases taken on as even a grid as is practical.

P, K and Mg levels are sensitive to differences in topsoil texture or natural pH, so zonal or 1 per ha grid sampling is advisable, especially on clay land. Zonal delineation requires soil survey because the national survey 1:250,000 maps are Associations, not Series, and thus are inadequate for predicting texture (or alkalinity); see WP2-10. Suggested revised RB209 wording is in Appendix.

Phosphorus

Short range variation of ±15% implies that areas measured at mid index 2 (20mg/l) typically span 17-23 mg P/l, with a bigger range under grassland or if the texture or SOM varies. Accordingly it is imperative to maintain topsoil P at (or above) 20 mg/l. This data shows this target is quite attainable, even on heavy land. On minimal till land, P status could also be checked 12-23cm to ensure this layer is not deficient.

A large proportion (37%) of the arable soils were P deficient while 32% had surplus P. This variation is despite promotion of RB209 over the past two decades which provides a method for equalising the index from either direction. Solving this would be helped by a texture refinement in the build or rundown amounts, ensuring faster builds for medium and heavier soils, and "safe" rundown allowances on high P soils to give farmers more confidence to omit phosphate fertiliser. See Appendix.

Regarding risks of P entering the watercourse, on light and some medium soils, above 35 mg/l (mid index 3) the P level in subsoil could rise sharply, due to some combination of organic matter movement by earthworms, historical deep ploughing or leaching. Providing erosion is controlled, higher P does not constitute an environmental risk *except in cases where the (lower) subsoil is affected by groundwater* or *is sandy/sandstone* with poor adsorption capacity. Nevertheless, because at high index there is usually a significant amount of P in subsoil as well as topsoil, it is very difficult to justify any fertiliser application at >35 mg/l except for some vegetable crops.

In clay subsoils P tended to be lower and could remain within index 0 even up to 35 mg/l topsoil P, though there were exceptions. Raised subsoil phosphate might increase risk of transmission to drains. However some Improvement of P status in clayey upper subsoils may benefit crop rooting and is achievable by earthworm activity encouraged by addition (incorporation) of organic manures and by appropriate subsoiling and drainage operations. The data here suggests that OM and P in subsoil decrease with depth, so the risk of transmission in under-drained soils is best ascertained by measuring P status *below 40cm depth*, not above. There is no risk on *well drained* heavy soils, e.g. over Chalk or Limestone.

Potassium

Short range variation of ±15% implies that a mid index 2- (150 mg/l) result typically spans a range of 125-175 mg K/l, with a bigger range where clay content varies significantly. Accordingly it is imperative to maintain topsoil K at (or above) 150 mg/l. This data shows this target is quite attainable, even on light loam soils.

Based on the common observation that *clinical* potassium deficiency is very likely in lower half of index 1 (90 mg/l), this might serve as a guide minimum for upper subsoil. 150-180 mg/l in topsoil usually guarantees the K in upper subsoil is above 90 mg/l, thus providing resilience in dry spring periods where crops become dependent on subsoil for their nutrient uptake. Where subsoil is very leaky (e.g. sandy, chalky or stony) there is an even stronger case for increasing the target in topsoil even if some leaching to subsoil is thus induced.

A large proportion (36%) of the arable soils and a greater % of grass leys were K deficient, while many samples had surplus (K index 2+ and 3), especially the Southern clays. As with phosphate, the wide range is despite RB209's design to move all soils to target index.

The report clarifies the clay types that supply 'free' potash that should reduce potash fertiliser requirement. Carboniferous clays have a poor K supply and were commonly deficient in topsoil and subsoil, Clay-with-Flints has a similar issue. The high releasing clays were Charmouth Clay (Lias) Oxford Clay, Kimmeridge and alkaline Glacial Till soils (Chalky Boulder Clay). Other clays seem to occupy an intermediate category, e.g. Triassic (red) clays, and the above-mentioned Clays where topsoil contained admixture of loamier material. A revised classification table is proposed in the Appendix.

Farmers could be helped utilise high K reserves and build where they are low, by some texture specificity in RB209 tables, e.g. faster builds on medium and heavy soils and safe run-down allowances that match the buffering or K release according to soil type. See appendix.

Though most clay subsoils seem OK (>90 mg K/l), the 40-50 kg/ha K_2O intercepts on plots bring into question whether a basal amount of K measured in heavier soils is not crop-available, which might warrant some further research trials.

There predictability of subsoil K from topsoil K is limited; and in some cases the subsoil may have been inordinately depleted by the previous crop(s). Therefore, on all potassium response trials it should be standard to measure K both in topsoil (to 20-25cm) and upper subsoil. On farm, subsoil testing might be considered where crops appear to be suffering K shortage despite adequate level in topsoil (e.g. low grain K). To remedy low subsoil K, ploughing under potash or manure is likely to be most effective, though over-application to the topsoil may succeed on lighter soils.

Magnesium

Of all the nutrients, Mg is affected most strongly by texture, and also by mineralogy and the Mg content of the lime used on farm.

Deficiency (index 1 or 0) is most common in the south, especially on arable land. Short range variation of ±15% implies that at 50 mg/l result typically covers a range 42-58 mg Mg/l,

Where index is 1, the potential for Mg deficiency is likely increased where the subsoil is sand, light loamy, stony (or chalky) because the subsoil reserve is likely to be lower than topsoil. On deeper medium and heavy soils the subsoil Mg is likely to be higher. Some clearer guidance is needed in RB209 as to when combinable crops warrant a Mg application at index 1. Some suggestions are in Appendix.

Ultra-high Mg soils (index 6-7) occur on red (Triassic) formations with dolomitic layers or Dolostone or alluvium over red clays. High Mg (index 4-5) is common on other clays.

To minimise risk of Mg induced K deficiency, Mg of index 6 or higher should be reduced if possible. Farmers on *Carboniferous* Clays especially should be wary of applying Magnesian limestone. On ultra-high Mg soils potassium target could be raised to index 2+ but some on-farm trials would help confirm this.

pH

This survey suggested pH levels were not too bad, possibly increased due to the greater sampling depth of topsoil than RB209. However there were many cases of low (yield-limiting) pH.

The data shows that in agricultural soils the subsoil pH is usually greater than the topsoil pH, supporting the maxim "look after the topsoil and the subsoil will look after itself". However there are exceptions, the upper subsoil is likely to be below pH 6 in the following cases, in which taking a pH test (20-40cm) may be beneficial on arable land.

- topsoil pH < 5.5 (heavy soils)
- topsoil pH < 5.8 (lighter soils)
- topsoil pH 6.0 or less. Areas that have not been limed within past 5 years.
- reinstated soils, subsoils containing coal fragments or organic layers (e.g. alluvium).

RB209 might be easier to use if it included the original ADAS calculation that underlies the lime rates cited, including a Lime Factor for subsoils. See appendix.

The subsoil's lime requirement is ideally ploughed under or could be added to the topsoil requirement or constitute a further application the following autumn.

For grassland the current depth of action of the recommendation is 15cm. Where topsoil pH is below 5.5 the lime rate could be increased to ensure deeper action.

Sampling depth for permanent grass might be increased from 7.5 to 10cm, and in multi-cut grass 15cm is always preferable for assessment of pH and K.

Many Southern deep clays and "Boulder Clay" soils are on the cusp of decalcification, pointing to the importance of accurate zonal delineation of calcareous and decalcified topsoils and/or pH testing on a hectare grid.

The acidification risk to all soils is reduced by utilisation of lime-containing products, and avoiding over-application of sulphur and nitrogen fertilisers.

Organic matter

This needs assessment by standardised sampling depths and protocols as mentioned above. Loss on Ignition methods are not suitable (for lowland soils).

Organic matter does not affect yields directly, but indirectly via improved workability, structural stability, phosphorus availability, potassium retention in light soils and stimulation of beneficial soil biota.

Rotational manuring is likely to maintain good earthworm population and may be more important than the level of organic matter per se.

Even so, RB209 could suggest SOM targets. This data would support minima of 2.5% for loamy sands, 3% light loams, 4% medium and 5% for clay-textured topsoils, with 2.5% being a good level for the upper subsoil.

Total nitrogen

Because C:N ratio varies, farmers should be encouraged to measure Total Nitrogen whenever they measure the Organic Carbon.

The relationship between C:N clay and nitrogen mineralisation warrants more research.

12. Work packages 1–3

Further sample analysis is provided in three additional work package reports.

Work package 1 (section A)

- East Midlands to South Yorkshire
- Carboniferous Sandstone, Siltstone and Mudstone

Work package 2 (section B)

- Leamington Spa to Crewe and Nottingham
- Red (Triassic) formations and overlying Drift

Work package 3 (section C)

- London to Leamington Spa
- Clay vales and ridges