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Cost-effective phosphorus management on UK arable farms

Grain Nutrient Benchmarking

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The Grain Nutrient Benchmarking (GNB) pilot (2017–18) forms part of a 64-month project (RD-2160004) that started in August 2013.

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Abstract

Over two seasons (2017 and 2018), farmers submitted 252 samples to a Grain Nutrient Benchmarking (GNB) pilot. Although the focus was to determine grain phosphorus (P) status, all grain nutrients were analysed. Here, the data are analysed, reported and discussed. The report also presents conclusions about the prospects for a routine GNB service.

More than half of the grain samples (59% of all cereals; 71% wheat) contained less than 0.32% P. In fact, P was clearly the nutrient most commonly showing apparent deficiencies. Nitrogen (N) was also commonly low – 38% of grain samples had less than 1.9% N. Other nutrients showing quite common apparent deficiencies were manganese (29%), potassium (~20%), sulphur (14%), molybdenum (12%) and zinc (8%).

Even though the majority of samples had less than the critical level of grain P, grain yield was not significantly associated with grain P. It may be the case, within this study, that factors other than P supply may have strongly affected grain yields. Nitrogen and manganese may also have been limiting and drought strongly affected crops in 2018.

Winter wheat had significantly lower grain P contents than barley (both winter and spring) and spring oats ($P<0.001$). Grain P in winter wheat did not differ from spring wheat, triticale or rye, although differences between species and varieties may appear when more data are available.

Grain P did not differ between seasons, but samples from the South East and the East Midlands had higher grain P than those from East Anglia ($P = 0.001$). Grain P showed a weak but positive association with soil P, and it was greater where a fertiliser blend, rather than DAP (di-ammonium phosphate), was used. However, probably due to the modest number of samples, there were no significant associations of grain P with soil pH, soil texture, cross-compliance soil group or use of organic manures.

It is concluded that routine grain analysis with benchmarking is feasible and would augment routine soil P analysis. Because most other nutrients are reported with grain P, routine grain analysis will be most useful if all grain nutrients are considered together. To date, routine grain analysis has not been used to support farm-scale crop nutrition. A service that shares data between clients is likely to hasten the development of norms, and should be a quick way to develop improved confidence in on-farm nutrient management for arable crops.

1 Introduction

Literature from overseas and the recent work in the Cost-Effective Phosphorus (P) Project (AHDB Report 570-3) showed that grain P% could diagnose crops that would have shown positive yield responses to additional P supplies. The critical value identified was 0.32% P in grain dry matter. It was concluded that routine field-by-field grain P analysis could be used to build confidence in overall farm P management, as it is currently informed mainly by soil P analysis. Analysis of >350 grain samples from the Yield Enhancement Network (YEN) showed a significant proportion of crops might be deficient (with values <0.32%), so an additional survey was set up by ADAS, with support from Yara and AHDB to check how easily a grain P monitoring service might be organised and how grain P analyses might augment soil P analyses e.g. how often crop deficiencies occur where soil P levels are deemed adequate, or vice versa.

2 Survey methodology

The grain nutrient benchmarking survey was open to all farms that were able to provide field-specific samples of any cereal crop harvested in 2017 or 2018. It was publicised through YEN Newsletters to sponsors and participants and in talks at the CropTec Show and AHDB Agronomists event in autumn 2017. In order to submit a sample for analysis farmers contacted ADAS who asked them to provide the following background information for each sample:

- Crop type, variety, planting season and yield (to the nearest t/ha)
- Field topsoil texture, soil pH, soil P, K and Mg Index (and date of soil analysis)
- Most recent applications of manufactured phosphate and potash, including date, type and rate
- Most recent applications of organic materials, including date, type and application rate.

For simplicity, farmers were asked to report the soil P, K and Mg Index of the field where the grain sample was grown, rather than the actual nutrient concentration. There were eleven possible categories for each nutrient, ranging from Index 0 to Index 9, with Index 2 further sub-divided into Index 2- and 2+. The Index groupings were in line with those the AHDB Nutrient Management Guide, with the exception of Index 2 for P and Mg, which was further sub-divided as noted previously. Farmers were also asked to report the soil pH of the field where the grain sample was grown; pH was grouped into four categories, i.e. pH <5, 5-6, 7-8 and >8. The farmers also reported the year from which the soil P, K, Mg and pH data originated.

Once the background information was received and verified, cereal grain samples were allocated a unique ID which was included on the pre-labelled bags that were provided to farms for submission of grain samples for free analysis by Yara[1]. Samples were analysed for nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), manganese (Mn), molybdenum (Mo), boron (B), copper (Cu), iron (Fe) and zinc (Zn). Grain nutrient concentrations were determined using inductively coupled plasma - optical emission spectrometry (ICP-OES)

Farm-specific data were reported to participating farmers through individual field reports, an example report is included in Appendix 1. All data were then collated and summarised in Excel spreadsheets and then analysis of variance and correlation analyses (using Genstat 19th Edition; VSN International, 2017) were used to assess relationships between grain nutrient levels and growing conditions. Prime attention was paid to grain phosphorus, since this was the main nutrient of concern when the Grain Nutrient Benchmarking exercise was initiated.

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3 Results

3.1 The dataset

In all, 252 grain samples were analysed from both seasons. There were no missing grain analyses and very few missing explanatory data (concerning location, genotype or growing conditions) because provision of these was a condition of sample acceptance. In this respect, this dataset is much more complete than data available from the YEN where descriptions of growing conditions are not always provided.

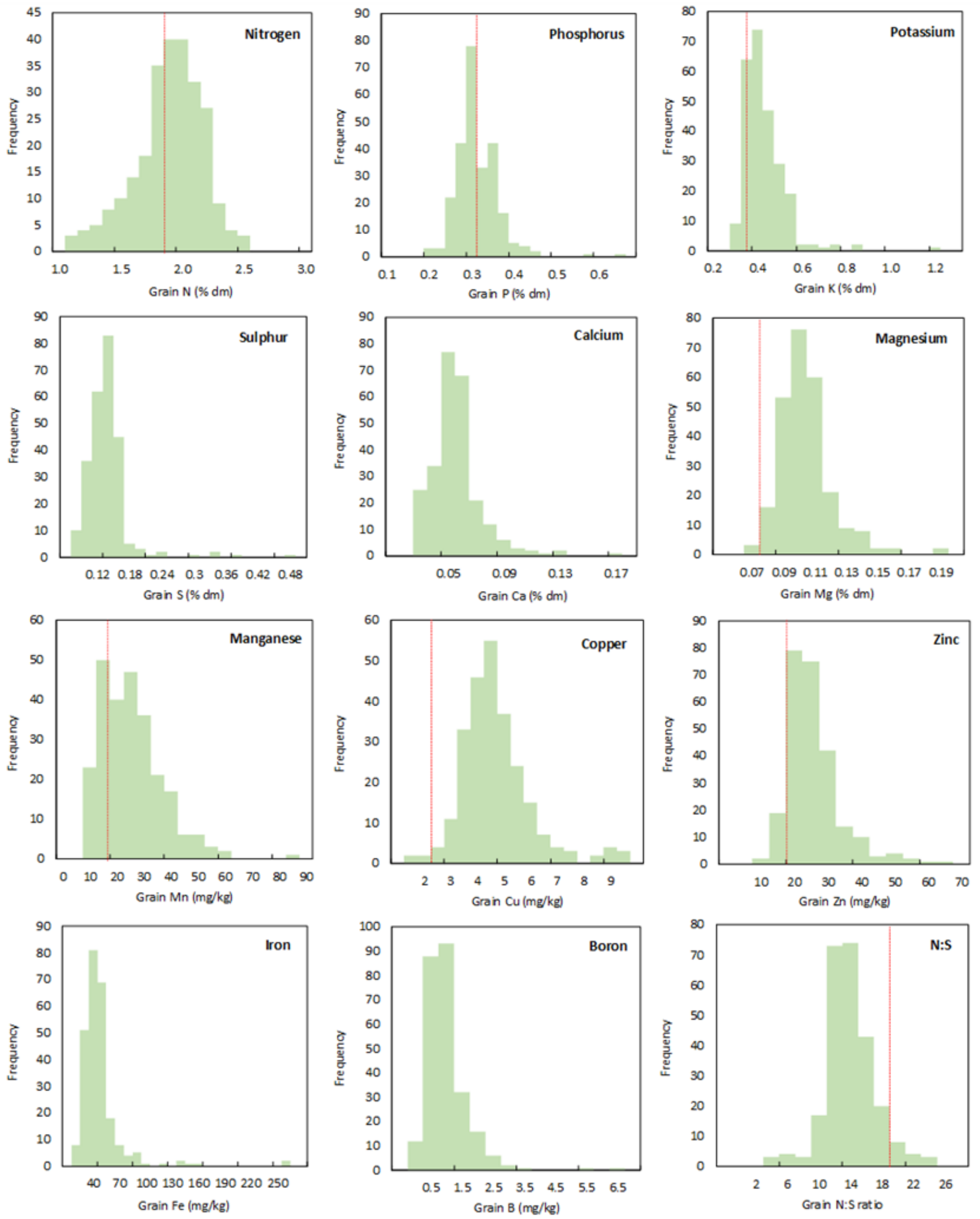

Figure 1. Occurrences of nutrient levels in all grain samples analysed from harvests 2017 & 2018. Dotted red lines show critical levels determined from recent UK research, and from the scientific literature.

Full summaries of each set of explanatory data, describing the range of growing conditions, and the datasets for each grain nutrient are provided in Appendix 2. The data for all grain nutrients are summarised in Figure 1, so that levels can be compared with critical values (vertical red lines), where these are known. The nutrient most commonly showing apparent deficiencies was clearly phosphorus (P) - more than half of the samples (59% of all cereals; 71% wheat) contained less than 0.32% P. N was also commonly low - 38% of samples had less than 1.9% N; however, for barley samples, this may have been influenced by quality requirements. Other nutrients showing quite common apparent deficiencies were Mn (29%), K (~20%), S (14%), Mo (12%) and Zn (8%) (Figure 1).

Given that the idea for this survey originated from research on P nutrition, and that P was the most commonly deficient nutrient revealed by grain analysis, the main focus of the results and discussion here is on grain P. However, the discussion starts with a broader overview of the whole dataset.

Note that it is conventional to express crop nutrient contents in relation to crop dry matter, and this is how GNB data are presented here. However, there are alternative ways of expressing nutrient concentrations such as inter-nutrient ratios (e.g. N:S) which may need to be considered in future.

In examining these data it is important to recognise that no causes of variation can be identified with certainty. The dataset has no predetermined structure so many aspects of the origin of each sample are confounded, and these factors cannot be disassociated with much certainty, given there were only a few hundred samples. It is also the case that farmers' choice of samples to submit may well have been influenced by discussions in the press and in recent meetings e.g. about recent research suggesting usefulness of grain analysis for identifying apparent P deficiencies; the sample-set may include a disproportionate number of samples from fields where farmers suspected P deficiencies. Thus this sample-set should not be treated as representative of UK arable farms, and only associations between growing conditions and grain characteristics can be identified; if these appear important, believable and useful, they nevertheless need to be validated by future experimentation.

3.2 Variation in growing conditions

About 60% of the samples were from harvest 2017 and 40% from harvest 2018. Samples were received from all of the main cereal growing regions of the UK. The majority were from the East of England (42%) or the East Midlands (19%), but samples were also received from the Southeast (15%), the Southwest (6%), Yorkshire and the Humber (8%), the West Midlands (1%) and Scotland (10%). There were 53 participating farms, 11 of which provided samples from both seasons, so assisting investigations into any possible 'farm effect'.

Grain yields ranged from less than 3 t/ha to more than 13 t/ha, so the samples represented wide ranging growing conditions: soil textures ranged from sands to clays and soil pHs from <6 to >8. Soil P, K and Mg Indices all ranged from 0 to 5 or more, so there was good scope to detect factors likely to be associated with grain nutrient levels.

3.3 Grain nutrient concentrations

Most grain nutrient concentrations tended to be positively correlated with each other (Table 1), albeit that most relationships only accounted for <15% of variance. It is likely that these positive inter-nutrient relationships were driven by variation in the success of grain filling; if most nutrient uptake occurs before grain filling and nutrients are largely redistributed to the grain during grain filling, it is likely that variable success of filling grains with carbohydrate will cause positive associations between grain nutrient concentrations. The two seasons contrasted in many respects and there were some seasonal effects on grain data, but yields were similar across the two seasons so seasonal effects on S, K, Ca, Mo and Fe were not driven by yield levels. Nevertheless there were some significant correlations of grain nutrients with grain yields, and also with soil nutrient levels e.g. Mg.

Both grain N and grain Mn were positively correlated with grain yield, indicating that these nutrients may have played some part in controlling yields. On the other hand, grain P, K, Mg and Zn were negatively related to yield, indicating that other factors were more important in controlling yield and that there was probably some dilution of these nutrients in the grain by formation of extra carbohydrate. The positive association with N:S ratio probably indicates that the N effect was more influential than any positive effect of sulphur. The lack of a relationship between grain P and yield is puzzling, given that the majority of grain P levels were deemed deficient by the new critical level. However, this presumably means that other factors were more important than P supplies in influencing grain yields. Grain P is now explored in more detail.

Table 1. Correlation coefficients for relationships between soil and crop characteristics of all cereal crops in the Grain Nutrient Benchmarking exercise. Statistically significant relationships are marked by light shading (P<0.05) or dark shading with bold text (*P*<0.01).

	Year	*Yield*	*Soil pH*	*Soil P*	*Soil K*	*Soil Mg*	*N*	*S*	*N:S*	*P*	*K*	*Ca*	*Mg*	*Mn*	*B*	*Cu*	*Mo*	*Fe*
Grain yield	-0.07																	
Soil pH	**0.21**	**0.20**																
Soil P	-0.09	-0.07	-0.04															
Soil K	-0.09	-0.01	0.07	**0.25**														
Soil Mg	-0.07	-0.13	-0.14	0.03	**0.36**													
Grain N	-0.02	**0.19**	**0.27**	-0.13	0.16	0.09												
Grain S	**0.32**	-0.02	**0.18**	0.02	0.12	-0.03	**0.21**											
N:S ratio	**-0.42**	**0.19**	-0.04	-0.02	-0.06	0.05	**0.31**	**-0.72**										
Grain P	-0.03	**-0.19**	-0.02	0.06	0.06	0.05	0.13	**0.29**	**-0.18**									
Grain K	**0.33**	-0.16	0.04	-0.03	0.00	-0.02	-0.03	**0.29**	**-0.25**	**0.67**								
Grain Ca	**-0.29**	-0.05	**0.19**	-0.12	0.03	-0.06	**0.19**	0.09	0.03	**0.35**	**0.28**							
Grain Mg	0.08	**-0.27**	-0.02	0.02	0.12	**0.30**	**0.21**	**0.26**	-0.15	**0.80**	**0.58**	**0.29**						
Grain Mn	0.07	**0.20**	**0.19**	**-0.21**	-0.12	**-0.27**	**0.29**	**0.22**	-0.05	**0.32**	**0.30**	**0.30**	0.06					
Grain B	0.14	0.06	-0.02	**-0.19**	0.02	0.07	0.11	0.01	0.07	**0.20**	**0.33**	0.16	**0.22**	**0.29**				
Grain Cu	-0.03	-0.05	-0.10	**-0.21**	**0.22**	**0.26**	**0.20**	0.15	-0.03	**0.29**	**0.32**	**0.36**	**0.43**	0.08	**0.31**			
Grain Mo	**0.34**	-0.10	**0.22**	0.00	0.07	0.08	**0.25**	0.10	0.01	**0.30**	**0.29**	0.09	**0.40**	-0.06	**0.17**	**0.24**		
Grain Fe	**-0.20**	-0.12	-0.04	-0.08	-0.05	-0.02	0.15	0.06	0.08	**0.36**	**0.25**	**0.54**	**0.31**	**0.30**	0.15	**0.24**	0.08	
Grain Zn	-0.16	-0.16	0.03	-0.03	0.13	**0.31**	**0.23**	0.13	0.02	**0.54**	**0.46**	**0.46**	**0.64**	**0.17**	**0.31**	**0.51**	**0.45**	**0.33**

3.4 Influences on grain P concentrations

3.4.1 Crop type and variety

The majority of the samples were winter wheat (77%); 12% were spring barley, 6% were winter barley; 2% were spring wheat; 2% were spring oats and 2% were other cereals (triticale and rye). For winter wheat samples that included information on variety, 54% were from milling varieties and 46% were from feed varieties (Table 2). More than 35 varieties were included in the wheat samples. However, six varieties made up more than 50% of the grain samples. Feed varieties were in a minority, possibly because samples were more likely to be retained on farms if crops were likely to attract a quality premium.

Table 2. Grain P contents (% dry matter) as influenced by cereal species and variety. (SD = standard deviation).

CROP & VARIETY	Nabim group	No. samples	Mean grain P%	SD
Winter Wheat		**195**	**0.30**	**0.049**
Skyfall	1	29	0.32	0.075
Gallant	1	5	0.31	0.032
Graham	4	8	0.31	0.023
Crusoe	1	17	0.31	0.026
KWS Trinity	1	5	0.30	0.016
Cordiale	2	5	0.30	0.041
Evolution	4	10	0.30	0.030
KWS Barrel	3	5	0.30	0.013
KWS Siskin	2	26	0.29	0.039
KWS Basset	3	5	0.28	0.023
KWS Lili	2	13	0.28	0.035
JB Diego	4	11	0.27	0.041
Zulu	3	6	0.25	0.019
Spring Wheat		**4**	**0.33**	**0.044**
Winter Barley		**15**	**0.34**	**0.046**
Spring Barley		**29**	**0.32**	**0.049**
Propino		7	0.36	0.055
RGT Planet		6	0.29	0.046
Concerto		6	0.29	0.012
Spring Oats		**4**	**0.35**	**0.066**
Triticale & Rye		**5**	**0.33**	**0.038**
All		**252**	**0.30**	**0.051**

Winter wheat had significantly lower grain P contents than barley (both winter and spring) and spring oats (P<0.001); grain P in winter wheat did not differ from spring wheat, triticale or rye (Table 2). A comparison, of the 13 winter wheat varieties with at least five samples showed that Skyfall and Crusoe (Group 1) had significantly higher grain P (P = 0.02) than Zulu (group 3). However, the range of grain P levels within a single variety meant that no other difference between varieties was noted. Nabim group 1 wheats (varieties used for bread making) had significantly higher grain P (P = 0.001) than wheat in either group 3 (soft varieties for biscuits, cakes etc.) or group 4 (mainly feed wheat).

If these genetic differences can be verified in experiments (e.g. by analysing grain from RL trials), the accuracy of and confidence in diagnoses of P deficient crops (on the basis of grain P) could be improved. Eventually recognition of genetic differences could also become useful in breeding more P-efficient varieties, and in formulating more P-efficient livestock feeds.

3.4.2 Season and region

There was no effect of season on grain P; means were 0.30% in 2017 and 0.29% in 2018. However, there was an effect of region on grain P; samples from the Southeast and the East Midlands had higher grain P than samples from East Anglia (*P* = 0.001) (Table 3).

Table 3. Grain P concentration (% dry matter) by UK region.

Region	Grain P, % DM	No of samples
Yorkshire & The Humber	0.28	14
Southwest	0.28	14
East Anglia	0.28	87
West Midlands	0.29	2
Scotland	0.30	7
East Midlands	0.30	41
Southeast	0.31	28

3.4.3 Soil factors

There was no significant associations of grain P with soil pH, soil texture or cross compliance soil group. Grouping the grain P data according to soil P Index showed that there was a positive association between grain P and soil P, grain P being higher in samples from sites at P Index 3 than at P Index 1 (*P* = 0.01) (Table 4). Regression analysis showed a quadratic function accounted for more of the variability in these data than a linear relationship (Figure 2).

Table 4. Grain P concentration (% dry matter) by Soil P index

Soil P Index	Grain P	No of samples
0	0.27	4
1	0.28	32
2-	0.29	35
2+	0.29	49
3	0.30	55
4	0.31	17
5	0.23	1

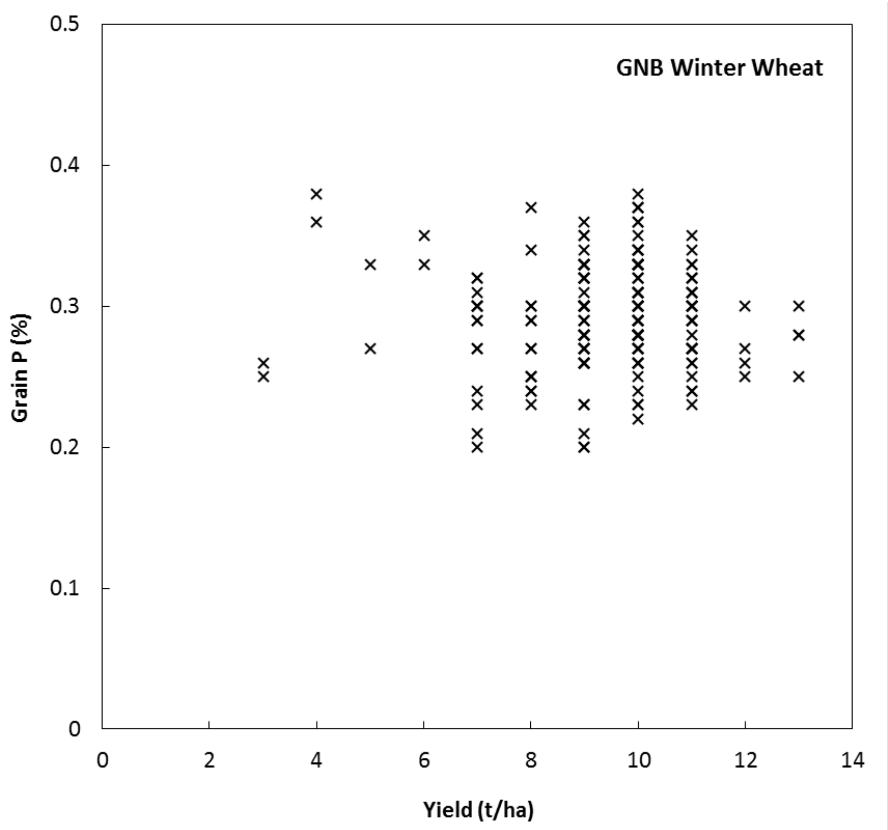

Figure 2. Relationship between grain P and grain yield in 2017 and 2018.

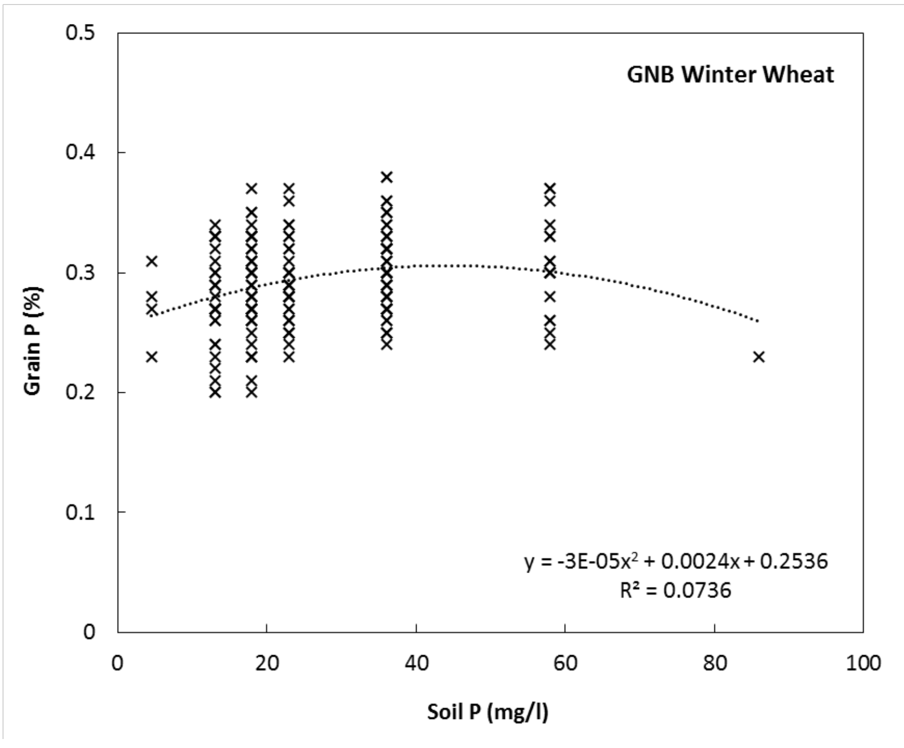

Figure 3. Relationship between grain P and soil P in 2017 and 2018.

3.4.4 Grain yield

The loose negative relationship between grain P and grain yield is shown in Figure 2. Even though experimentation with soil P supplies has shown a critical grain P concentration of 0.32%, several other factors probably affected these results:

- Grain yield was positively associated with N and Mn so, within these crops, supplies of N and Mn are likely to have been more influential than supplies of P.
- High P supply may have its main effect at only one phase of the growing season - say during establishment, before root systems and mycorrhizal associations have developed - so this initial association will become masked by other factors that apply during other phases of growth.

3.4.5 P fertiliser type and rate

Grain P was not significantly greater where P fertilisers had been applied, and there was no association between grain P concentration and P fertiliser application rate. However, the data showed higher grain P where a fertiliser blend rather than DAP (di-ammonium phosphate) had been used (P = 0.006) (Table 5).

Table 5. Average grain P concentration by P fertiliser type in GNB samples from 2017 and 2018.

Soil P Index	Grain P, % DM	No. of samples
No P fertiliser	0.29	49
Di-ammonium phosphate	0.28	26
Triple superphosphate	0.29	68
Blend	0.31	50

3.4.6 Organic materials

There was no association between the grain P concentration of wheat samples and applications rates or type of organic materials applied.

4 Discussion and Conclusions

This exercise was set up to explore the practical and theoretical potential of using grain nutrient analysis to provide a routine post-mortem of the nutritional status of individual commercial crops, with a particular focus on phosphorus. The initial discussion will therefore focus on what this survey implies for the use of grain P in the P management of land growing cereal crops. However, because grain P analysis involves use of the ICP technique, which also provides results for most other crop nutrients, grain analyses have considerable extra potential value, so the discussion also considers issues governing the feasibility and value of operating a multi-element grain nutrient benchmarking service.

4.1.1 Grain P as a diagnostic of P sufficiency:

Recent AHDB-funded research has shown a new critical P limit in grain of 0.32% (or 3,200 mg/kg or 3.2 g/kg; Sylvester-Bradley *et al.*, 2019). This level was the same for a whole series of past and current P response experiments in the UK, and for many experiments in Scandinavia, so it seems quite reliable i.e. grain P levels of less than 0.32% in these experiments indicated that the crop would have produced a worthwhile yield response if extra P uptake could have been effected. Also, grain P levels of more than 0.32% indicated that responses to extra P uptake would have been small and uneconomic. More than half the cereal crops reported here had less than 0.32% P in their grain. Furthermore, a recent report from the YEN states that about one quarter of crops assessed from that network had P levels of less than this critical level, even though many of these crops were chosen to be high yielding.

These results clearly raise the question of whether a substantial proportion of UK arable crops are being grown with inadequate capture of P? If the grain P threshold can be taken as robust this seems likely to be true. Extreme low grain P values of 0.20% would be associated with reductions in grain yield of more than 2 t/ha, whilst values of 0.25% would indicate losses of ~1 t/ha and 0.30% would mean losses of 0.5 t/ha (Figure 4). However, this conclusion would be difficult to validate because of the very low efficiency of most P fertilisers (recent research found commonly used P fertilisers e.g. TSP, give best crop P recoveries of <10% and average recoveries were <5%). Fertiliser P comparisons are therefore unable to show whether crops are deficient unless treatments with no added P are compared with treatments where a very large amount of fertiliser P has been applied.

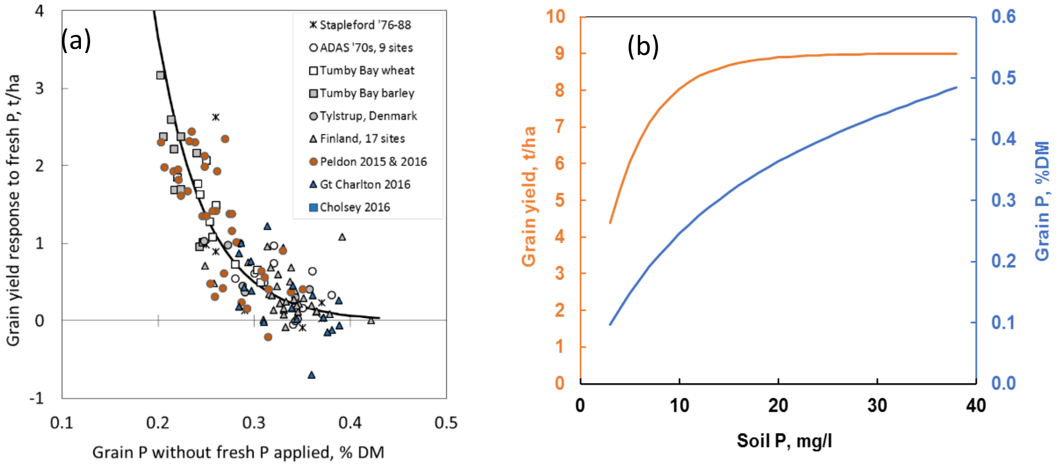

Figure 4. (a) Fitted relationship between levels of grain P and yield responses achieved by comparing differences in soil P (caused by applying large quantities of fertiliser P) and (b) inferred 'typical' relationships between soil P, grain yield and grain P (from Sylvester-Bradley *et al.*, 2019).

The absent or weak association between grain P and grain yields in these datasets is probably compatible with the levels of yield losses associated with the deficiencies - these losses are small compared to all other yield variation (Figure 2) - so P supplies could probably not be expected to be dominant amongst the large number of other factors influencing grain yields, both unpredictable and predictable (see recent analysis by Sylvester-Bradley & Kindred, 2019). We therefore conclude that P deficiencies are likely to be present and influential, whilst being hidden by more dominant factors such as weather, region, soil type, rotation, and particularly 'the farm-factor'. Indeed, soil P may constitute part of 'the farm-factor'.

As expected there was an association between grain P and soil P but there were several other factors at play; as more data become available it should prove possible to describe these with more confidence and take them into account when interpreting grain P data. Thus there will be value to arable farmers, as they start making use of grain P analysis, in sharing their data and being able to see analyses of the combined dataset. Eventually, variation in grain P must be expected to relate to several factors such as weather during the growing season (which will affect crop growth and rooting depth), water availability (e.g. water deficient conditions such as those of summer 2018 are likely to have reduced P availability), other soil factors (e.g. structural conditions and organic matter content) and cultivations.

4.1.2 Grain Nutrient Benchmarking

As well as frequent P deficiencies, low levels of other nutrients were shown in quite a few samples, judging by critical levels taken from the literature; these included K, Mg, S, Mn and Zn.

This finding and previous research has prompted the notion of farmers using chemical grain analysis as a routine component of their nutrient management practices. Comprehensive and routine grain analysis to inform good crop nutrition is a new and largely unused notion (except for grain N or grain protein assessments; Sylvester-Bradley & Clarke, 2009) which appears to hold significant promise in terms of usefulness, if its operation and interpretation can be facilitated. However, there are significant issues involved in routine grain nutrient benchmarking. First is the ease with which representative grain samples can be collected at harvest time. The number of samples submitted in this exercise was ample for our purposes, but was not as large as expected; discussion with growers showed that, whilst some did take and keep separate grain samples from individual fields (for confirmatory intelligence in support of grain trading) most were not in the habit of doing so. If grain benchmarking is to work, we suppose that it will be important to ease the process of taking, keeping and despatching such samples to analytical laboratories at the busy harvest time. Luckily, there has been previous very thorough HGCA-funded work to establish good grain sampling practices (Hook, 2004), so it will be important to learn the lessons from this.

Secondly, the initial issues with interpretation of multi-nutrient analyses of grain appear to be in having sufficient standards or comparators so that assessments of low, moderate or high nutrient levels can be made easily and with confidence. Experience with the YEN shows that this can be facilitated by collating the wide-ranging datasets available, and adding-in new data as it becomes available. This approach has been termed 'benchmarking'. Whilst reliable threshold values indicating boundaries between nutrient deficiency and sufficiency have not necessarily yet been determined for some nutrients, grain nutrient analysis could nevertheless be immediately useful in a commercial context if sufficient contemporary data could be made available against which results from an individual field could be compared.

Thirdly, the basis of expressing nutrient concentrations needs careful consideration; individual grain nutrients are held in quite different concentrations within the tissues of the grain (testa, endosperm, scutellum, radicle, plumule, etc.; Wu *et al.,* 2013); some, like P, are concentrated mainly in the scutellum, whilst others like Ca are mainly within the seed coat and others like sulphur and nitrogen are held more in the starchy endosperm. Whilst grain nutrient values are expressed conventionally as proportions of total dry matter, these values are inevitably influenced by the extent to which the grain's endosperm has filled with starch. An alternative may be to express nutrient levels in relation to each other rather than to dry matter, so that deficiencies can be detected with more consistency. An approach like this has been developed and used over many years in other world regions; termed DRIS ('the Diagnosis and Recommendation Integrated System'; Walworth & Sumner, 1987), this has so far only been applied to nutrient concentrations in leaf tissues, not those in grain. When sufficient grain data have been collated, there will be a case for a review of the best approach to nutrient expression in grain. This would be particularly enhanced if experimental data can be found testing contrasts in individual nutrients, where grain nutrient levels have been measured.

Although interpretation of grain nutrient levels is relatively uncertain at present, it will be developed fastest if much data can be collected and collated as quickly as possible, and if some care is applied to its expression. There will therefore be value in sharing data from routine grain analysis from the outset. With the advent of cloud-held databases this should be relatively straightforward to arrange. Indeed, a similar approach might also be considered and investigated for interpretation of other routine analyses, such as of leaf and soil nutrient levels (Rollett *et al*., 2017).

Clearly it will also be important to ensure that grain nutrient analyses are consistent between commercial labs. Although no direct comparisons can be made here, it should be noted that NRM[2] analysed samples from 2017 and 2018 (from YEN entries) whilst Yara[3] analysed samples from the same two seasons through the GNB exercise reported here. No clear differences were seen between the overall average values obtained (Table 6), although there was perhaps a tendency for levels of most nutrients to be less for the GNB samples; this could easily have arisen because the YEN and the GNB samples were not selected with similar intentions.

Table 6. Average nutrient contents in dry matter of all grain samples received from harvests in 2017 & 2018 from two different labs: NRM for YEN and Lancrop for GNB.

	N %	P %	K %	S %	Ca %	Mg %	Mn ppm	Cu ppm	Zn ppm	Fe ppm	B ppm
YEN	2.11	0.30	0.44	0.15	0.05	0.10	30	5	27	50	1.2
GNB	2.09	0.34	0.41	0.13	0.04	0.09	27	4	23	41	1.6

4.1.3 Conclusions:

Our conclusion is that the industry could straightaway adopt and start extending the use of routine grain analysis, in order to help manage crop nutrition. Grain P analysis has particular value because soil P analysis is less precise than soil analysis for K or Mg. However, grain analyses in the YEN show that results for all of N, P, K, Mg, N:S, Mn, Cu and Zn can probably be taken as indicative of crop nutrient status. (Ca and Fe are less meaningful, and B is clearly unreliable at present.) So it seems well worthwhile for growers to opt for a full-spectrum grain nutrient analysis service. The £30 spent per field would almost certainly be recouped by better identification of nutrient shortages - or, if all appeared OK, by peace of mind.

Grain sampling is a much easier way of getting a representative picture of overall nutritional conditions in a field than soil sampling. And if you have both soil and grain analyses, you can deduce whether crops had adequate rooting, or achieved inadequate uptake, despite having adequate soil supplies. For most nutrients (not Ca) the grain contains most of the crop's uptake of that nutrient, so for example, grain analysis enables accurate determination of nutrient offtakes and allows more accurate management of those nutrients (P and K) that depend on building soil reserves.

Like soil analysis, grain analysis is inherently an 'end of term' report; it provides strategic information about the nutrient status of the field; it is less relevant to decisions on tactical nutrient applications during crop growth (which are best supported by leaf analysis). Clearly grain analysis is not an alternative to soil analysis; but grain analysis tells us more than just soil analysis. If deficiencies are detected in the absence of low soil levels, then poor rooting and/or moisture supplies must be suspected.

We also conclude that growers opting for routine grain analysis should subscribe in a new way. Instead of submitting single samples to a laboratory and getting single results back, growers will get

[2] NRM laboratories, Coopers Bridge, Braziers Lane, Bracknell, Berkshire RG42 6NS, UK.

[3] Yara Analytical Services (Lancrop Laboratories) Wellington Road, the Industrial Estate, Pocklington, York, YO42 1DN, UK.

far more value from their nutrient analyses by permitting comparisons or 'benchmarking' of their own results with everyone else's. In other words, they would see their individual values for each of the nutrients, set against the backdrop of the information shown in Figure 1.

The value of this approach arises because, other than for N and P, no certain thresholds exist for interpretation of nutrient sufficiency from grain analysis in the UK. Sharing information within a new Crop Nutrient Benchmarking network will not only provide an immediate assessment of relative crop nutritional status, but eventually it can develop precise critical nutrient levels. Where low nutrient levels are detected, the following crop in their rotation will usually be treated and, in time, intelligence on responses to nutrient additions could become shared and collated. Thus more and more information will accumulate to indicate critical values, and ultimately ensure better crop nutrition.

Histograms, such as in Figure 1, are possibly difficult for farmers to interpret, if they have results from many fields. However, experience with communicating benchmarking information in the YEN has helped to develop new formats for reporting, such as is illustrated in Figure 5.

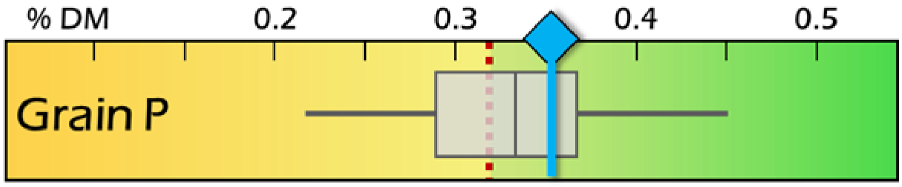

Figure 5. Benchmarking diagram designed to enable easy referencing of a client's result (blue diamond & line) against the middle half (grey box), median (vertical grey line) and range (horizontal grey line) of values in the population chosen for comparison, and the critical value (red dotted line). Buff and Green shading indicate the extents to which values differ undesirabley or desirably (respectively) from the critical value.

5 Acknowledgements

We acknowledge funding from AHDB and provision of free grain nutrient analysis from Yara Analytical Services (Lancrop Laboratories). We are also grateful to all the farmers who collaborated.

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7 Appendix 1. Example Farmer Report from 2017

Grain Nutrient Benchmarking

Entrant's Report

Harvest 2017

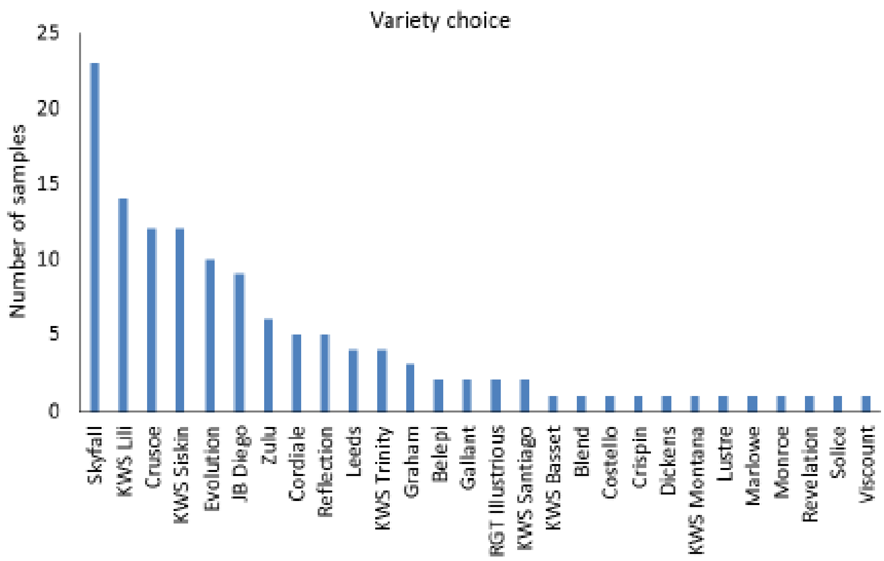
Field name:
Crop:

GNB Field ID:
Variety:

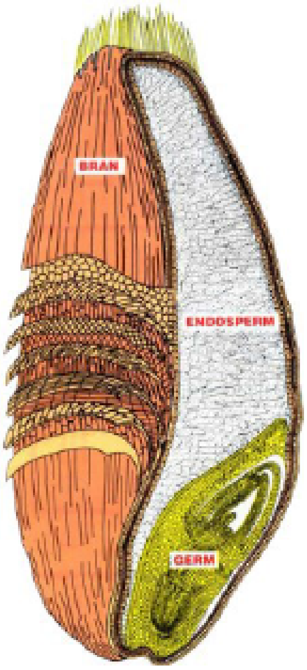
Overview

For harvest year 2017, *c.*200 cereal grain samples were analysed for the following nutrients: nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, manganese, molybdenum, boron, copper, iron and zinc.

The majority of the samples were winter wheat (*c.*80%); for those samples that included information on variety 66% were from milling varieties and 34% were from feed varieties. Wheat samples came from 28 varieties, however, six varieties made up almost 50% of the grain samples (see chart below).



Crop Nutrition



Nitrogen (N) and sulphur (S) are primarily used to form endosperm proteins. These, and the mineral nutrients in grain (contained mainly in the bran or germ), may usefully be taken to reflect the nutritional history and status of the crop through its life.

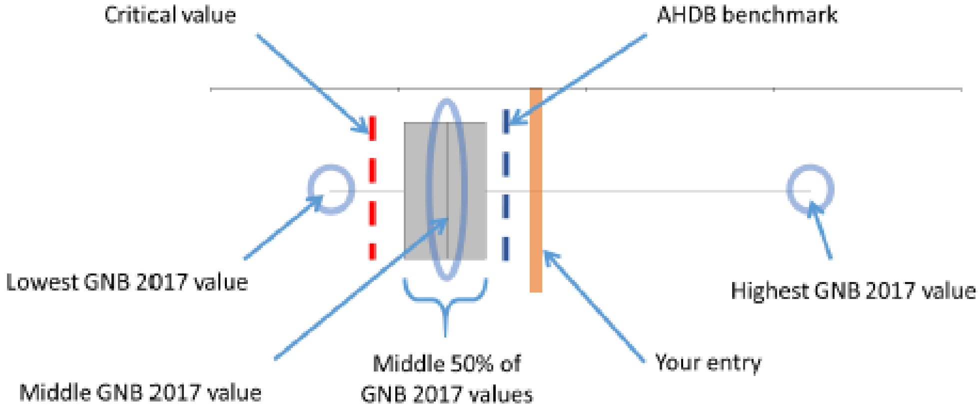
The literature suggests 'critical' concentrations in grain for a few nutrients, but for all nutrients it is possible to relate their individual levels to all other nutrients in the sample, and all other GNB samples, hence indicating which nutrients were most limiting.

Reliable low limits (critical levels) in grain are only available for N, S and now phosphorus (P). However, from the following bar-charts, you should be able to identify the nutrient(s) most likely to have limited your crop by comparing with the mid-level in all the other GNB samples.

Diagram showing the structure of a wheat grain; most nutrients other than N and S are held in the bran (e.g. K, Mg), or germ (e.g. P).

GNB Bar charts – What do they mean?

The bar-charts will help you compare your value with everyone else's and with critical values, if available, as follows:



The 'whiskers' show the range of GNB values in 2017 (e.g. grain P values ranged from 0.20-0.45%) and the box shows the middle half of GNB values, with a line for the mid-value. The orange line shows the value for this entry, and the red line is a limit beyond which yield may be adversely affected; crops with values beyond these merit further investigation.

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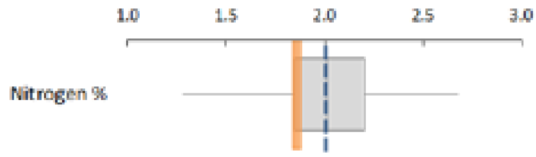
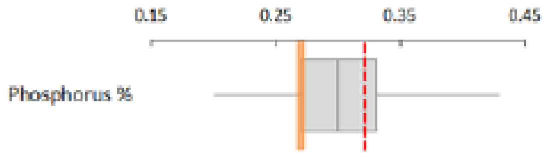
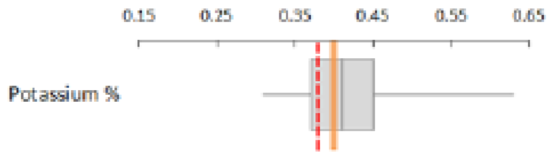


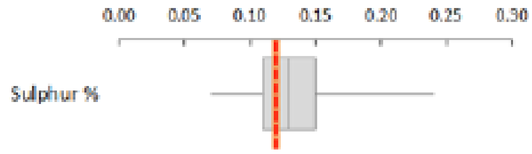
The majority of nitrogen in wheat grains is held in the endosperm as the storage proteins, gliadins (providing dough extensibility) and glutenins (providing dough elasticity).
NB: AHDB Benchmark is 1.9% N for barley (value for wheat is shown).



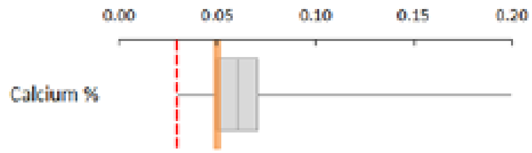
Recent AHDB research has shown grain P analysis can provide a useful check on whether a field is providing sufficient phosphorus. Values less than 0.32% indicate a need for further checks.



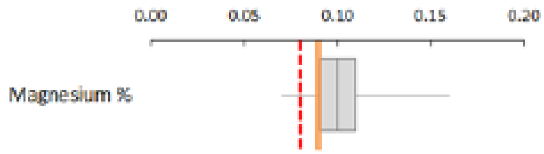
RB209 assumes a standard value of 0.55% K in grain. Values less than 0.38% indicate a need for further checks on K nutrition, especially by soil analysis.



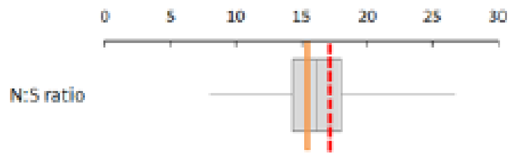
Grain sulphur is important for storage protein formation, especially the glutenins. Sulphur is required in proportion to grain protein formation, hence N supplies; low grain S is <0.12%.



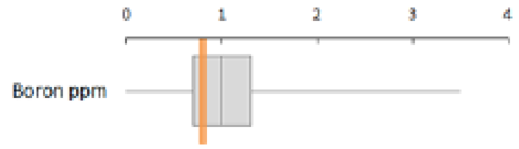
Plant calcium levels tend to reflect adequacy of moisture supplies. Almost all the plant's calcium remains in the straw at harvest. Grain calcium is mainly in the seed coat/bran; low grain Ca is <0.03%.



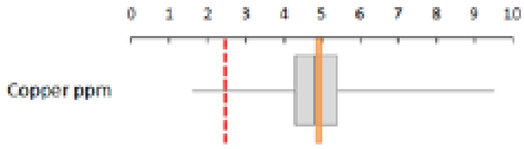
With further experience, grain magnesium levels may provide a useful double check on soil levels and crop symptoms. Literature shows low values in grain are <0.08%.



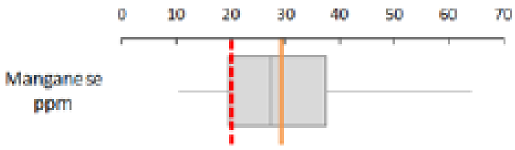
High N:S ratios (greater than about 17) indicate likely S deficiency



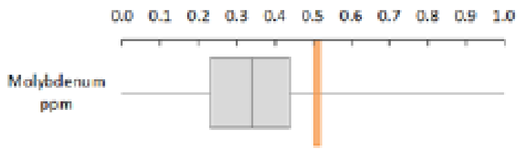
Grain analysis may not be a useful way of assessing boron sufficiency.



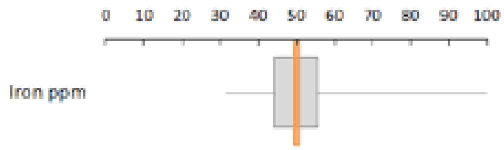
Grain copper <2.5 ppm indicates possible deficiency.



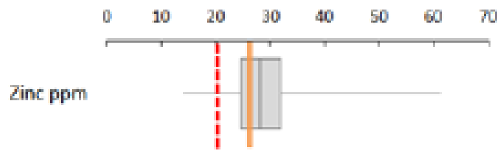
As with Magnesium, further experience with grain manganese levels may provide a useful double check on results of leaf analysis and any leaf symptoms. Literature shows low values in grain are <20 ppm



Whilst grain molybdenum may prove useful, we currently have no guidelines for its interpretation



Whilst grain iron may prove useful, we currently have no guidelines for its interpretation.



Zinc values <20 ppm are low but whether these should be regarded as limiting is uncertain.

Harvest 2018

A further *c.*250 grain samples from harvest 2018 will be analysed for the nutrients listed above (i.e. nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, manganese, molybdenum, boron, copper, iron and zinc).

Details of how to enter your samples into next year's GNB are on the following page.

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8 Appendix 2. Data summaries

8.1 Variation in growing conditions

8.1.1 Soil texture

Soil texture: Clay loam (32%), silty clay loam (19%) and sandy clay loam (18%) were the most common soil types (Figure 6). In total eleven soil textural classes were represented.

Information on soil texture was used to allocate soils to cross compliance soil groups as follows: 15% heavy (CL, SC and ZC), 71% medium (SCL, CL and ZCL) and 15% sandy and light (S, LS, SL, SZL and ZL).

Soil texture (% of sample)	
Clay (CL)	10
Sandy clay (SC)	2
Silty clay (ZC)	3
Sandy clay loam (SCL)	19
Clay loam (CL)	32
Silty clay loam (ZCL)	19
Sand (S)	2
Loamy sand (LS)	1
Sandy loam (SL)	9
Sandy silty loam (SZL)	3
Silty loam (ZL)	<1

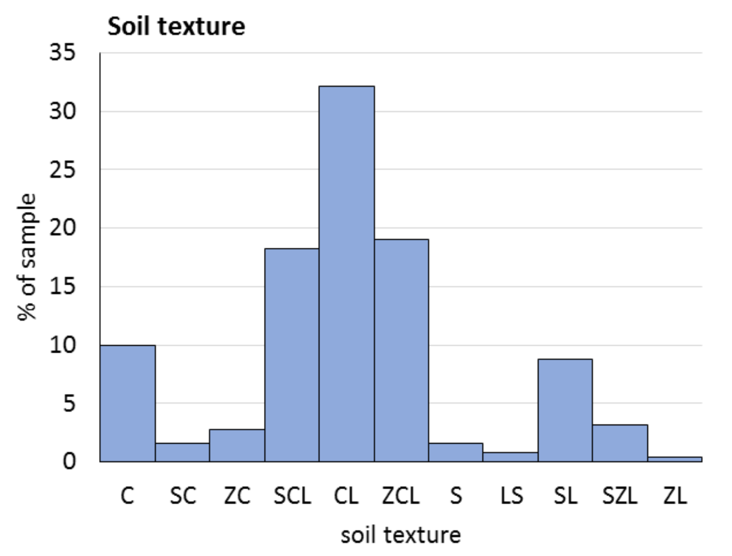

Figure 6: Soil texture of fields where GNB crops were grown (% of sample) in 2017 and 2018.

8.1.2 Soil P, K and Mg Index and pH

Reported soil P ranged from P Index 0 to P Index 5 (Figure 7). 40% of the samples were from fields at the target soil P Index for arable crops of Index 2 (16-25 mg/l); of the 40%, 24% were at the lower end of the range (i.e. 16-20 mg/l) and 16% were at the upper end (i.e. 21-25%).

40% of the samples were from fields at soil P Index ≥3 and 20% were at soil P Index ≤1.

Soil P Index/mg/l	
0	0-9
1	10-15
2-	16-20
2+	21-25
3	26-45
4	46-70
5	71-100

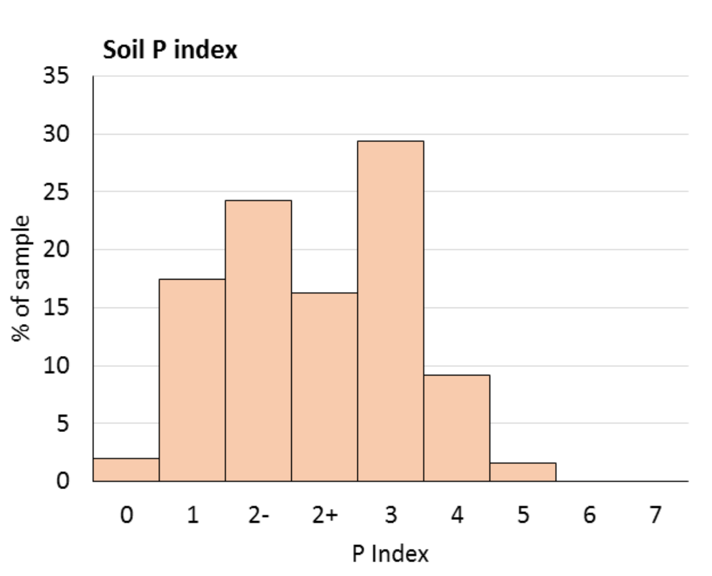

Figure 7: Soil P Index of fields where GNB crops were grown (% of sample) in 2017 and 2018.

Reported soil K ranged from K Index 0 to K Index 5 (Figure 8). 27% of the samples were from fields at the target soil K Index for arable crops of Index 2- (121-180 mg/l). In comparison, 36% of samples were from fields at K Index 2+ and in total 66% of the samples were from fields at soil K Index ≥2+ and 8% were at soil K Index ≤1.

Soil K Index/mg/l	
0	0-60
1	61-120
2-	121-180
2+	181-240
3	241-400
4	401-600
5	601-900

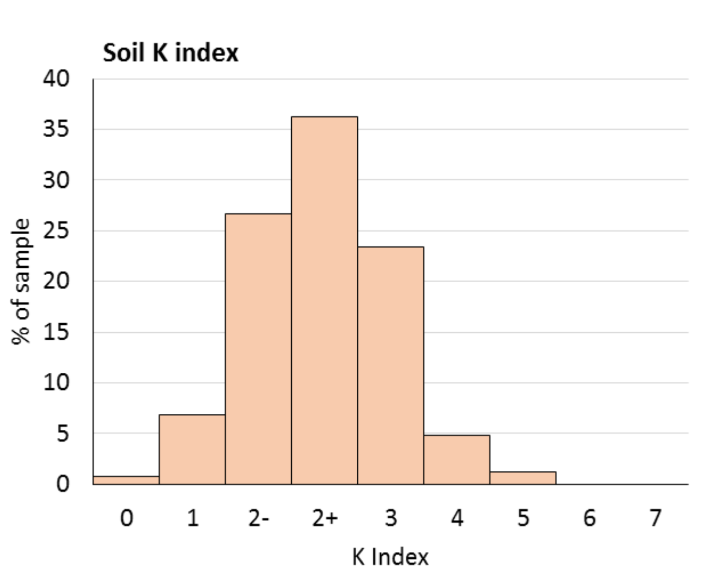

Figure 8: Soil K Index of fields where GNB crops were grown (% of sample) in 2017 and 2018.

Reported soil Mg ranged from Mg Index 0 to Mg Index 7 (Figure 9). 43% of samples were at Mg Index 2-/2+, 18% were from fields at Mg Index ≤1 and 40% at Mg Index ≥3.

Soil Mg Index/mg/l	
0	0-25
1	26-50
2-	51-75
2+	76-100
3	101-175
4	176-250
5	251-350
6	351-600
7	601-1000

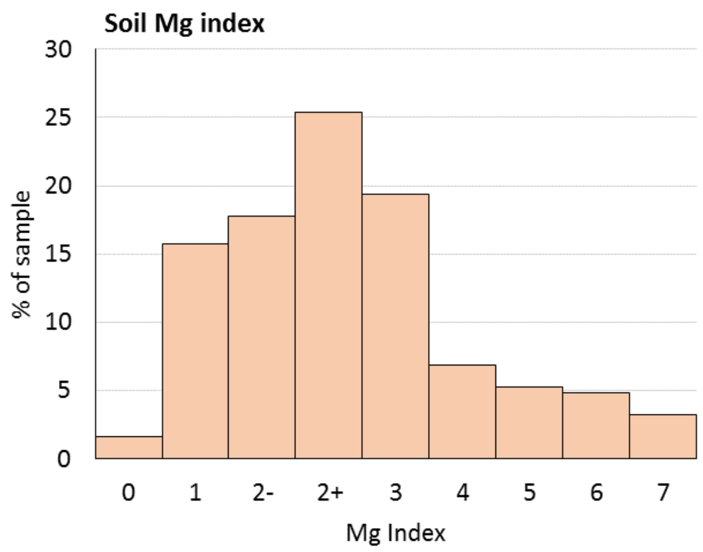

Figure 9: Soil Mg Index of fields where GNB crops were grown (% of sample) in 2017 and 2018.

According to the AHDB Nutrient Management Guide, the target pH for continuous arable cropping is pH 6.5; 26% of samples were reported as pH 6-7. Most fields (68%) had pH greater than the target pH, whilst 6% had pH less than the target (Figure 10).

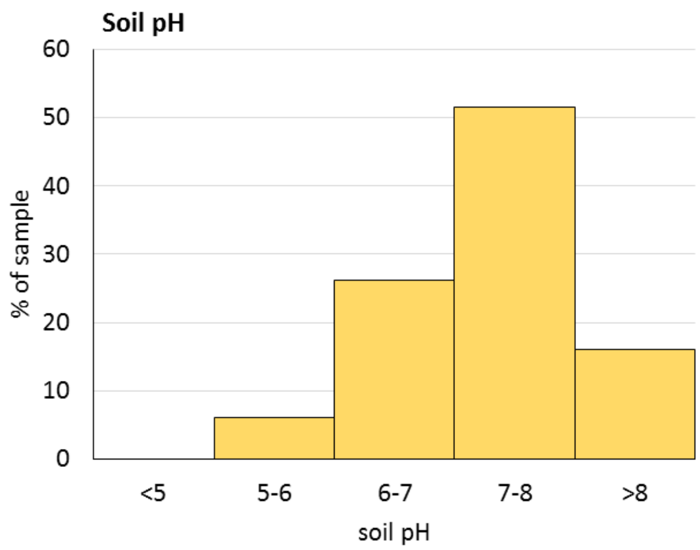

Figure 10: pH of fields where GNB crops were grown (% of sample) in 2017 and 2018.

8.1.3 Manufactured P and K fertiliser applications.

Triple super phosphate (TSP) was the most commonly applied P fertiliser (33%) and Muriate of Potash (MOP) was the most commonly applied K fertiliser (39%) (Table 7). More than a quarter (28%) of farmers reported using no P fertiliser and more than a third (39%) used no K fertiliser.

Table 7. Type of P and K fertiliser applied to 2017 and 2018 GNB fields (% of sample)

P Fertiliser	% of sample	K Fertiliser	% of sample
Triple superphosphate	33	Muriate of potash	39
Blend	28	Blend	22
Di-ammonium phosphate	12	None	39
None	28		

Of the farmers who had used P fertiliser 85% had applied it within the last two years: 38% reported their most recent P application was in the same year as the grain sample was taken, 29% the previous year and 18% two years before.

Reported phosphate and potash application rates ranged between 15 and >150 kg P_2O_5/ha (Figure 11). Of the farmers who applied P, more than half applied ≤50 kg P_2O_5/ha. For potash, application rates were more varied, overall more than half of the farmers who applied K, applied ≤90 kg K_2O/ha (Figure 11).

Similarly, of the farmers who had used K fertiliser 94% had applied it within the last two years: 55% reported their most recent K application was in the same year as the grain sample was taken, 26% the previous year and 13% two years before.

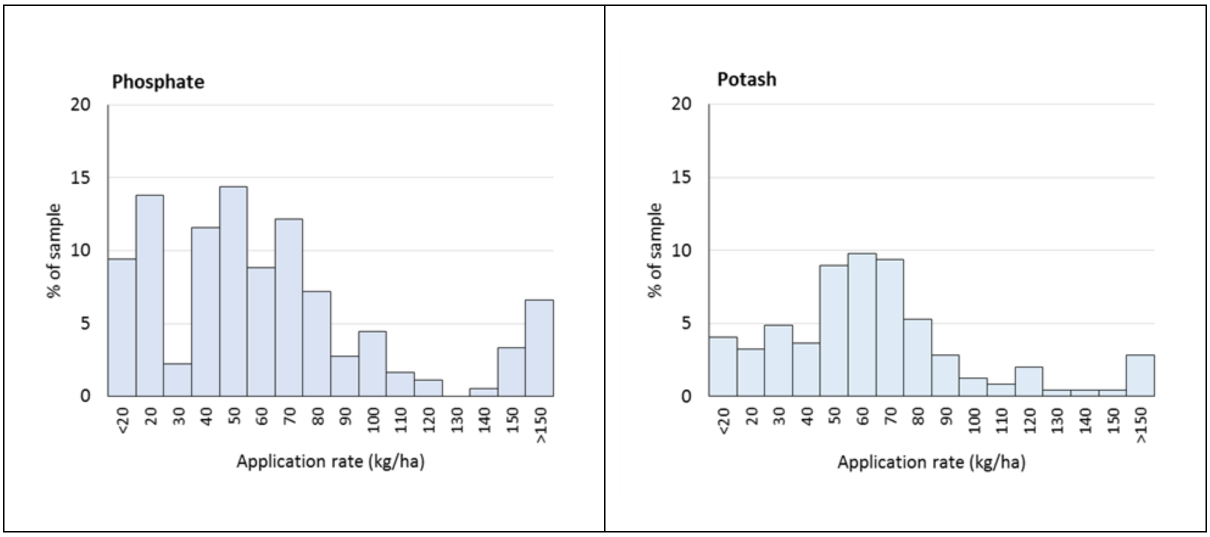

Figure 11. Application rates (kg/ha) of phosphate (P_2O_5) and potash (K_2O) (% of sample) for those fields that had received manufactured P_2O_5 or K_2O since 2010.

8.1.4 Organic material applications

Just over half (52%) of the farmers had applied organic manures, with a wide range of manure types reported (Figure 12). 75% of organic materials were applied at an application rate of ≤20 t/ha. Of the farmers who had used organic manures 80% had applied them within the last two years: 15% reported their most recent application was in the same year as the grain sample was taken, 45% the previous year and 19% two years before.

Organic manure	% of sample
Biosolids	13
Broiler litter	6
Layer manure	6
Compost	6
Pig slurry	5
Other	5
Cattle FYM	4
Pig FYM	4
Digestate	2
Cattle slurry	1
None applied	48

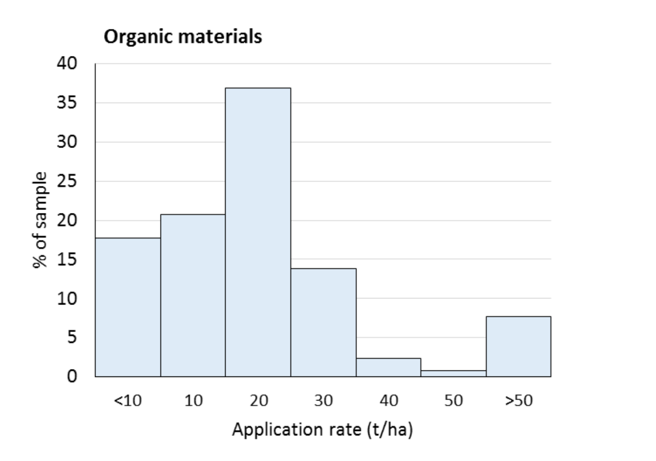

Figure 12. Organic manure types and application rates (kg/ha) of organic materials (% of sample) for those fields that had received manufactured organic materials since 2010.

8.2 Grain nutrient analyses

Nitrogen (N): Mean grain nitrogen was 2.04 ± 0.03% dry matter (dm) with a range of nitrogen concentrations from 1.21-2.68% dm (Figure 13).

At the economic optimum rate of nitrogen application, grain N is about 1.9% for feed wheat and 2.1% for milling wheat; 33% of milling wheat had grain N <2.1% and 25% of feed wheat had grain N of <1.9%.

Nitrogen	
Mean	2.04
Min	1.21
Max	2.68
St dev	0.28
SEM	0.02
95% CI	0.03
Lower CI	2.01
Upper CI	2.07

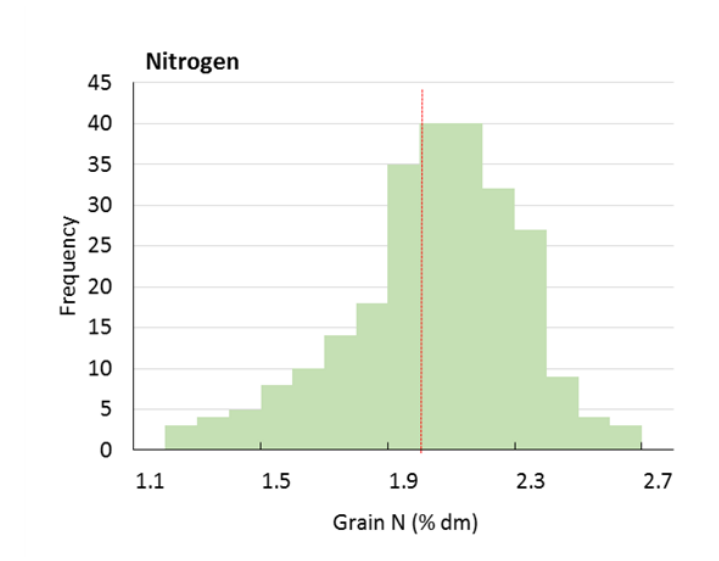

Figure 13. Occurrence of grain nitrogen-N (% dry matter-dm) in GNB samples (2017 and 2018).

Phosphorus (P): Mean grain phosphorus was 0.30 ± 0.01% dm with a range of phosphorus concentrations from 0.20-0.65% dm (Figure 14).

Values of less than 0.32% in dry matter indicate a need for further checks on P nutrition; 65% of samples were below this level.

Phosphorus	
Mean	0.30
Min	0.20
Max	0.65
St dev	0.05
SEM	0.003
95% CI	0.01
Lower CI	0.30
Upper CI	0.31

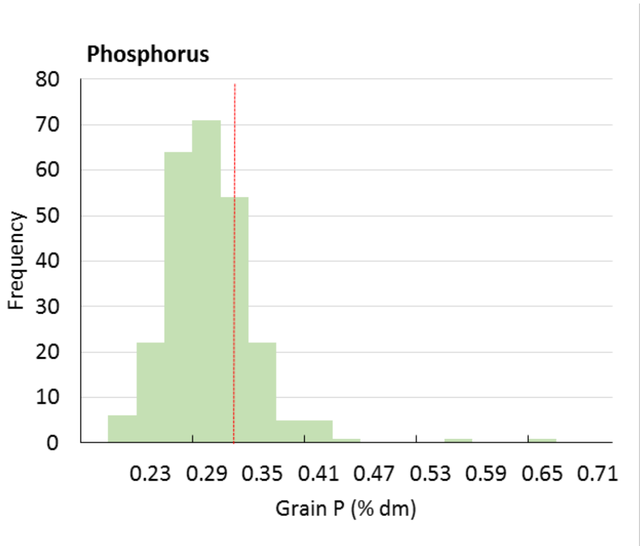

Figure 14. Occurrence of grain phosphorus-P (% dm) in GNB samples (2017 and 2018).

Potassium (K): Mean grain potassium was 0.45 ± 0.01% dm with a range of potassium concentrations from 0.30-1.24% dm (Figure 15).

Values of less than 0.38% in dry matter indicate a need for further checks on K nutrition; 17% of samples were below this level.

Potassium	
Mean	0.45
Min	0.30
Max	1.24
St dev	0.10
SEM	0.01
95% CI	0.01
Lower CI	0.44
Upper CI	0.46

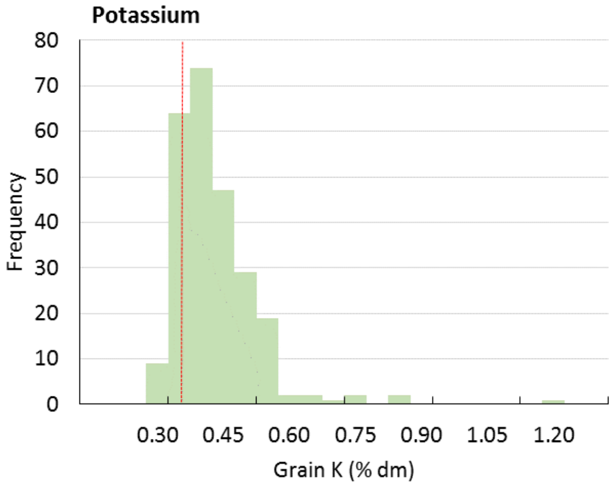

Figure 15. Occurrence of grain potassium-K (% dm) in GNB samples (2017 and 2018).

Sulphur (S): Mean grain sulphur was 0.14 ± 0.01% dm with a range of sulphur concentrations from 0.09-0.49% dm (Figure 16).

It has been suggested that values of less than 0.12% in dry matter indicate a need for further checks on S nutrition; 18% of samples were below this level.

The mean N:S ratio was 15 ± 0.4 with a range of N:S ratios from 4-25 (Figure 17). An N:S ratio >17:1 suggests that the crop may have suffered from sulphur deficiency; 13% of samples had an N:S ratio greater than this value.

Sulphur	
Mean	0.14
Min	0.09
Max	0.49
St dev	0.04
SEM	0.003
95% CI	0.01
Lower CI	0.14
Upper CI	0.15

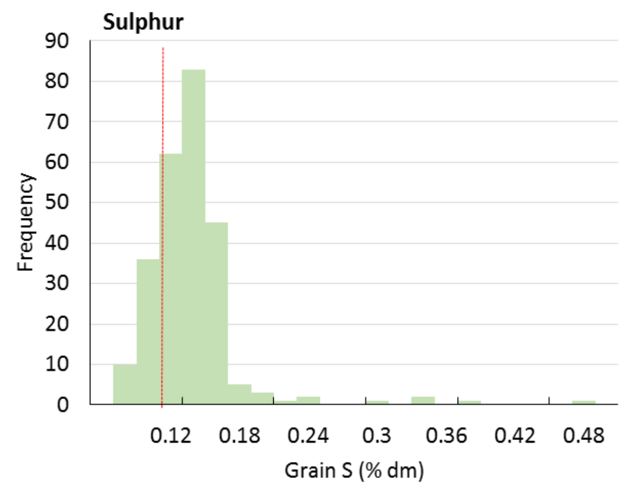

Figure 16. Occurrence of grain sulphur-S (% dm) in GNB samples (2017 and 2018).

N:S ratio	
Mean	15
Min	4
Max	25
St dev	3.14
SEM	0.20
95% CI	0.39
Lower CI	14.5
Upper CI	15.3

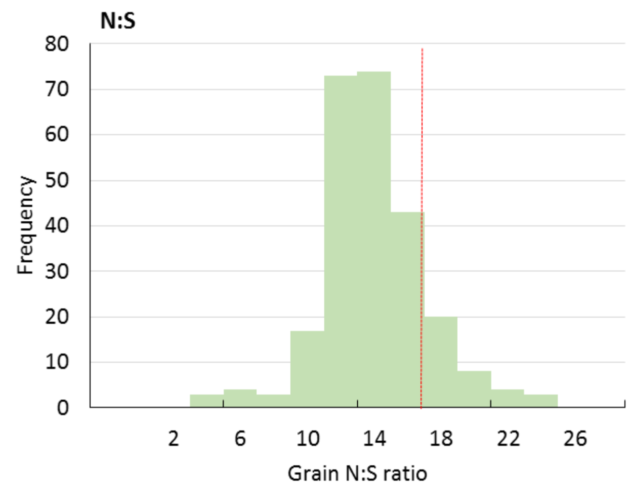

Figure 17. Occurrence of grain nitrogen-N to sulphur-S ratio (% dm) in GNB samples (2017 and 2018).

Magnesium (Mg): Mean grain magnesium was 0.10 ± 0.002% dm with a range of magnesium concentrations from 0.07-0.20% dm (Figure 18).

Low grain Mg is <0.08%; 1% of samples were below this level.

Magnesium	
Mean	0.10
Min	0.07
Max	0.20
St dev	0.02
SEM	0.001
95% CI	0.002
Lower CI	0.10
Upper CI	0.11

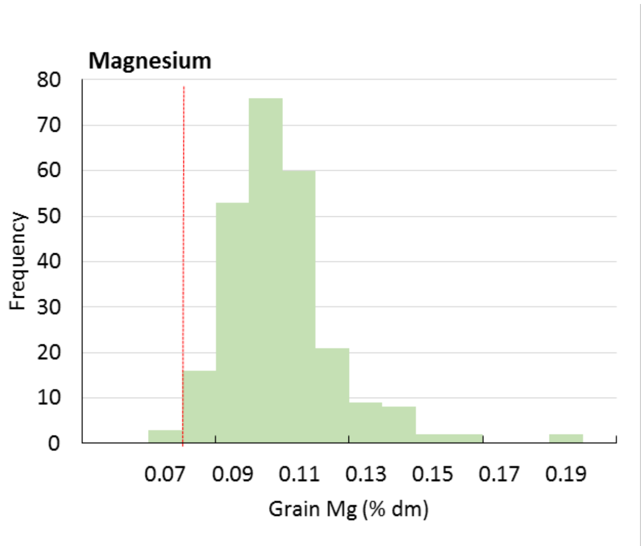

Figure 18. Occurrence of grain magnesium-Mg (% dm) in GNB samples (2017 and 2018).

Calcium (Ca): Mean grain calcium was 0.06 ± 0.002% dm with a range of calcium concentrations from 0.03-0.18% dm (Figure 19).

Low grain Ca is <0.025% dm; all samples were above this level.

Calcium	
Mean	0.06
Min	0.03
Max	0.18
St dev	0.02
SEM	0.001
95% CI	0.002
Lower CI	0.05
Upper CI	0.06

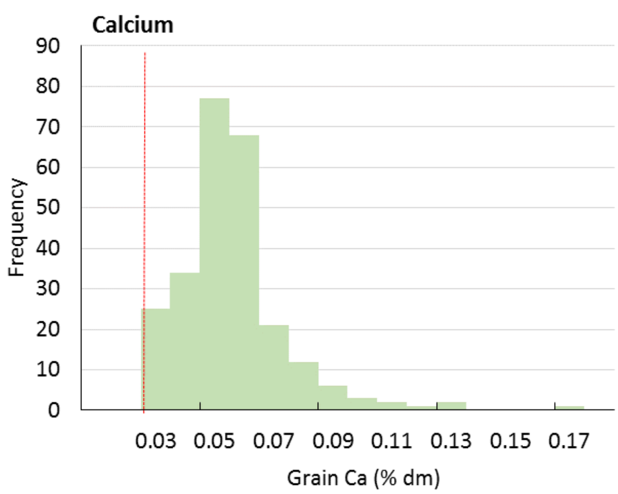

Figure 19. Occurrence of grain calcium-Ca (% dm) in GNB samples (2017 and 2018).

Manganese (Mn): Mean grain manganese was 27.7 ± 1.42 mg/kg dm with a range of manganese concentrations from 10.1-86.9 mg/kg dm (Figure 20).

Low values in grain are <20 ppm although it is not known if this represents deficiency; 29% of samples were below this level.

Manganese	
Mean	27.7
Min	10.1
Max	86.9
St dev	11.4
SEM	0.72
95% CI	1.42
Lower CI	26.2
Upper CI	29.1

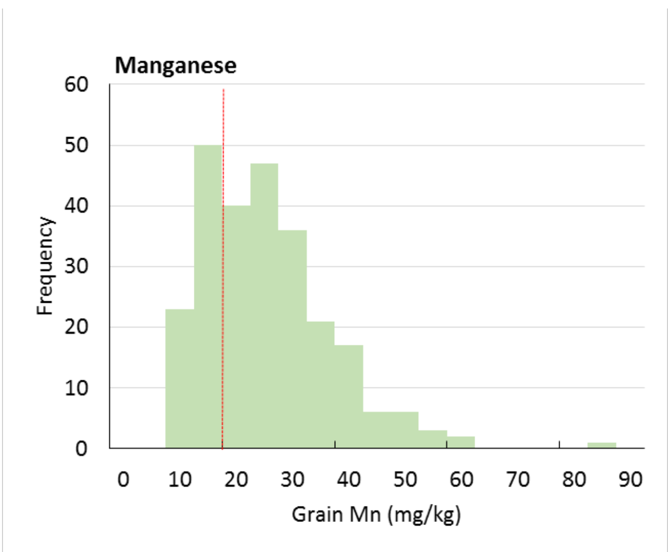

Figure 20. Occurrence of grain manganese-Mn (% dm) in GNB samples (2017 and 2018).

Boron: Mean grain boron was 1.21 ± 0.09 mg/kg dm with a range of boron concentrations from 0.30-6.80 mg/kg dm (Figure 21). There are currently few guidelines to assess critical values in grain.

Boron	
Mean	1.21
Min	0.30
Max	6.80
St dev	0.72
SEM	0.05
95% CI	0.09
Lower CI	1.13
Upper CI	1.30

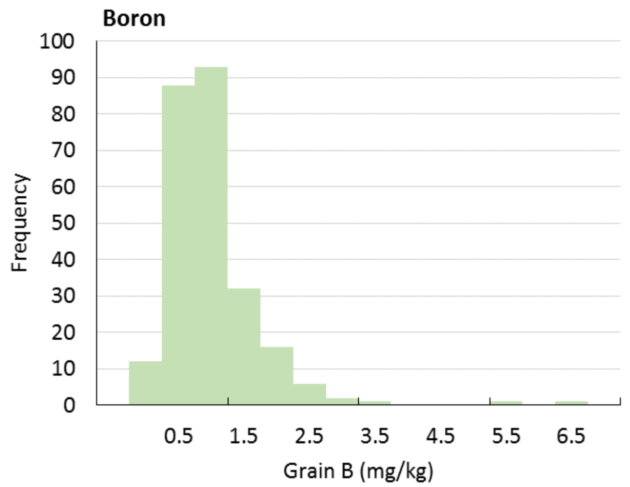

Figure 21. Occurrence of boron-B (% dm) in GNB samples (2017 and 2018).

Copper (Cu): Mean grain copper was 4.89 ± 0.16 mg/kg dm with a range of copper concentrations from 1.60-9.80 mg/kg dm (Figure 22).

Grain Cu <2.5 ppm indicates possible deficiency; 2% of samples were below this level.

Copper	
Mean	4.89
Min	1.60
Max	9.80
St dev	1.33
SEM	0.08
95% CI	0.16
Lower CI	4.72
Upper CI	5.05

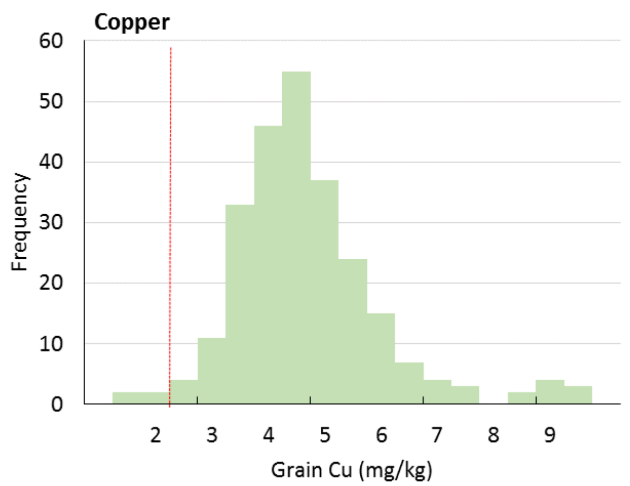

Figure 22. Occurrence of copper-Cu (% dm) in GNB samples (2017 and 2018).

Molybdenum (Mo): Mean grain molybdenum was 0.48 ± 0.04 mg/kg dm with a range of molybdenum concentrations from 0.05-2.08 mg/kg dm (Figure 23). There are currently few guidelines to assess critical values in grain.

Molybdenum	
Mean	0.48
Min	0.05
Max	2.08
St dev	0.29
SEM	0.02
95% CI	0.04
Lower CI	0.44
Upper CI	0.51

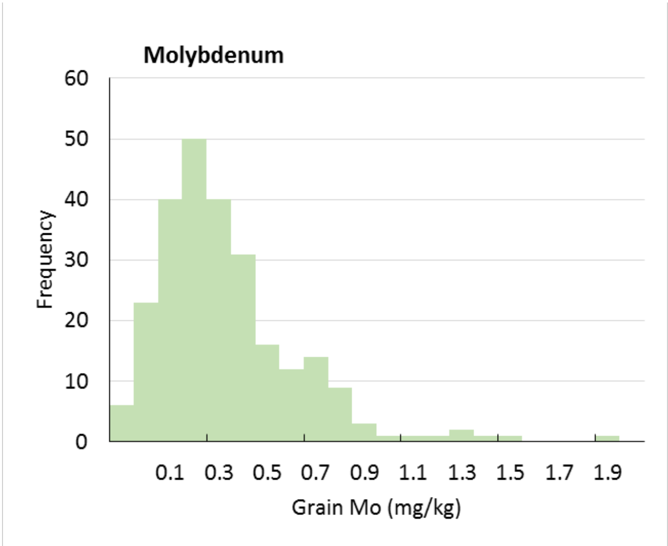

Figure 23. Occurrence of molybdenum-Mo (% dm) in GNB samples (2017 and 2018).

Iron: Mean grain iron was 53.1 ± 3.37 mg/kg dm with a range of iron concentrations from 23.3-266 mg/kg dm (Figure 24). There are currently few guidelines to assess critical values in grain.

Iron	
Mean	53.1
Min	23.3
Max	266
St dev	27.2
SEM	1.71
95% CI	3.37
Lower CI	49.7
Upper CI	56.4

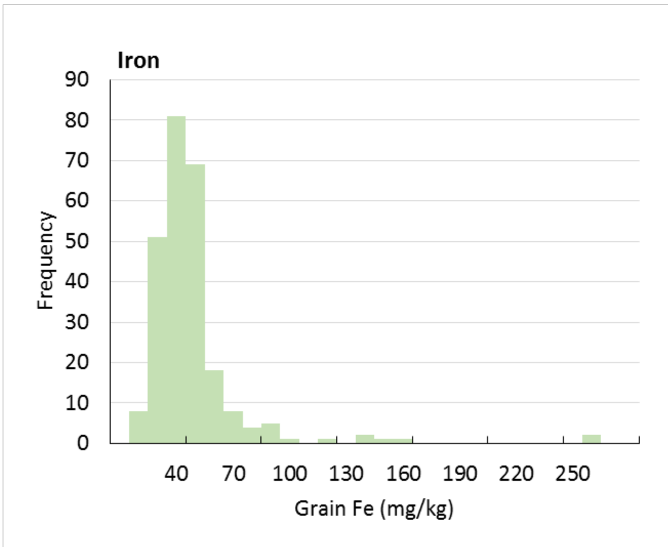

Figure 24. Occurrence of iron-Fe (% dm) in GNB samples (2017 and 2018).

Zinc (Zn): Mean grain zinc was 28.1 ± 1.01 mg/kg dm with a range of zinc concentrations from 14.0-68.2 mg/kg dm (Figure 25).

Low values in grain are <20 ppm although it is not known if this represents deficiency; 8% of samples were below this level.

Zinc	
Mean	28.0
Min	14.0
Max	68.2
St dev	8.14
SEM	0.51
95% CI	1.01
Lower CI	27.0
Upper CI	29.0

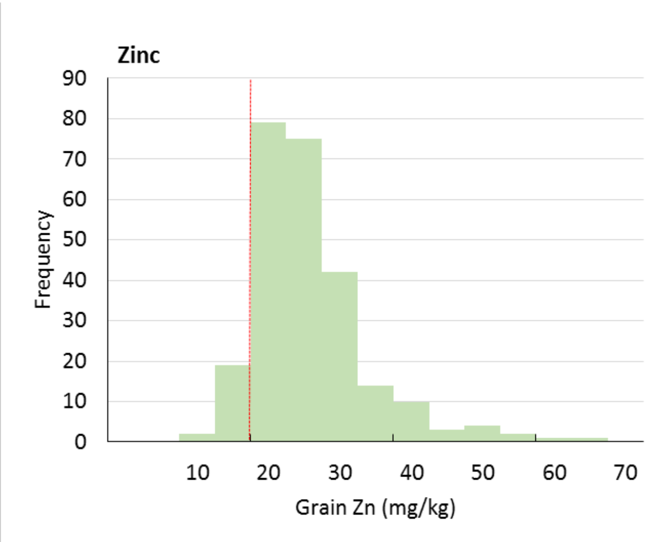

Figure 25. Occurrence of zinc-Zn (% dm) in GNB samples (2017 and 2018).