Review

Potash Requirements of Potatoes

Project Ref: R443

Report Authors: Peter Dampney (ADAS) (Lead author), Stuart Wale and Alex Sinclair (SAC)

Report No. 2011/4

The Potato Council is a division of the Agriculture and Horticulture Development Board.

Additional copies of this report and a list of other publications can be obtained from:

Publications

Potato Council
Agriculture & Horticulture Development Board
Stoneleigh Park
Kenilworth
Warwickshire
CV8 2TL

Tel: 02476 692051
Fax: 02476 789902
E-mail: publications@potato.org.uk

Our reports, and lists of publications, are also available at www.potato.org.uk

CONTENTS

1. SUMMARY

- Potash is an essential nutrient for potato growth, and large quantities of potash (K_2O) are applied for potatoes either as manufactured fertiliser and/or in organic manures. The average application of manufactured potash fertiliser in Britain between 2005 and 2010 was 221 kg K_2O/ha, which at current prices would cost c. £122/ha. Organic manures are applied to c.35% of the potato cropped area and are a valuable source of potash and other nutrients – a typical application of FYM will supply c.300 kg K_2O/ha of potash. However, data from the British Survey of Fertiliser Practice shows that when fertilising potatoes, growers typically allow for less than 10% of the potash content of organic manures applied for the crop.

- Current standard potash recommendations are based on the need to replace the amount of potash removed in tubers in order to maintain the soil K level at the target maintenance level (Index 2 in England and Wales, soil status M in Scotland). The SAC recommendations for potatoes grown in Scotland only take account of the possible response of potato yield and quality to potash. Because of concerns about tuber quality, the recommended rate to be applied before planting does not take account of the potash removed in tubers. Although many trials, albeit mostly now quite old, have shown tuber yield responses to potash, especially at low soil K Indices, these responses have usually been quite small and to potash rates that are less than the amount of potash needed to replace potash removal in tubers. It is concluded that there is no evidence to support higher potash rates than are needed for replacing the removal of potash in tubers, based on a potash offtake of 5.8 kg K_2O/ha.

- In current recommendations, the quantity of potash removed in tubers is calculated using the standard offtake figure of 5.8 kg K_2O per tonne of tubers. The evidence base for this offtake figure commonly makes use of old data on low yielding and outdated varieties. There are a wide range of offtake values quoted in the literature with little evidence to identify the causes of the variation. Continued use of the 5.8 kg K_2O/t offtake figure is recommended as the basis for potash use on potatoes.

- Research suggests that application of potash at rates for maximum yield is sufficient to minimise the risk of bruising (blackspot). The use of higher rates to achieve further reduction gives benefits that are too small and inconsistent to be of practical value. The effect of potassium on Enzymic Browning was not large, and was mainly observed on soils that were low or deficient in potassium. The effect of potash on fry colour has been variable, with the largest improvement in fry colour coming from low rates of applied potash. The effect of potash on After-Cooking Darkening is variable and other climatic and management factors may be more important. Overall, the research evidence suggests that levels of potash that give optimum yield, and are sufficient to replace potash offtake, are also sufficient to reduce quality defects. There is no evidence to indicate that higher rates provide any consistent or significant improvement.

- In some areas where magnesian lime has been used in the rotation for decades as the usual and local source of agricultural lime, soil Mg Indices can be very high (Index 5 and over) with the ratio of soil K:Mg (mg/l) less than 0.5:1. There are strong anecdotal suspicions that potassium shortages can be induced on these soils and that higher rates of potash may be needed. It has been estimated that around 13% of the potato area might be grown on these soils.

- The following research requirements are identified:
    - To determine the potash content in tubers of modern potato varieties, and to study the crop and field factors that influence variability in this offtake. The results will provide a more robust basis for potash planning for potato crops and in potato rotations.
    - To study the yield and quality response of potatoes to the rate, form and timing of potash (and other nutrients) under modern potentially ‘high nutrient efficiency’ growing systems (e.g. irrigated, bed system, destoned, placed fertiliser), compared to older probably ‘lower nutrient efficiency’ systems which represent most of the current research evidence base.
    - To study if the high potash recommendations (for tuber quality) made by some processors are required. These recommendations are currently above the potash rates required to replace potash offtake.
    - To study the potash requirements of potatoes grown on soils with a high magnesium (Mg) content where high soil Mg can restrict the uptake of potash by the crop. Significant areas of potatoes are grown on these soil types.

2. INTRODUCTION

In UK agricultural production systems, additions of potash (K_2O) as manufactured fertiliser or organic manure are usually needed during the rotation to help realise the full crop production potential of farmland, and to maintain the nutrient fertility of the soil. The amount needed depends mainly on the soil type, soil fertility, and cropping. In contrast to nitrogen and phosphorus, the application of potash to land has no adverse impacts on the water, air or soil environments.

Potassium (K) is a recognised nutrient that is known to be essential for the growth of crop plants, including potatoes. In the plant, some potassium is used as an activator of enzymes, to control stomatal opening and to regulate the movement of other nutrients and products of photosynthesis through the plant (Hewitt 1983). Much larger amounts of potassium are involved in regulating water within the plant and in maintaining the rigidity (turgor) of plant cells so that they function efficiently in capturing sunlight to produce sugars (Milford and Johnston, 2007). Large quantities of potassium are taken up by the potato crop, about one and a half times as much as nitrogen (N), and 5-6 times more than phosphorus (P). It is generally accepted that the uptake of potassium is greatest in mid-season and then declines to harvest, as illustrated in Figure 1 (DGER/SCPA, 1992). Potassium is also implicated in some tuber quality requirements which are important for end-users and processors.

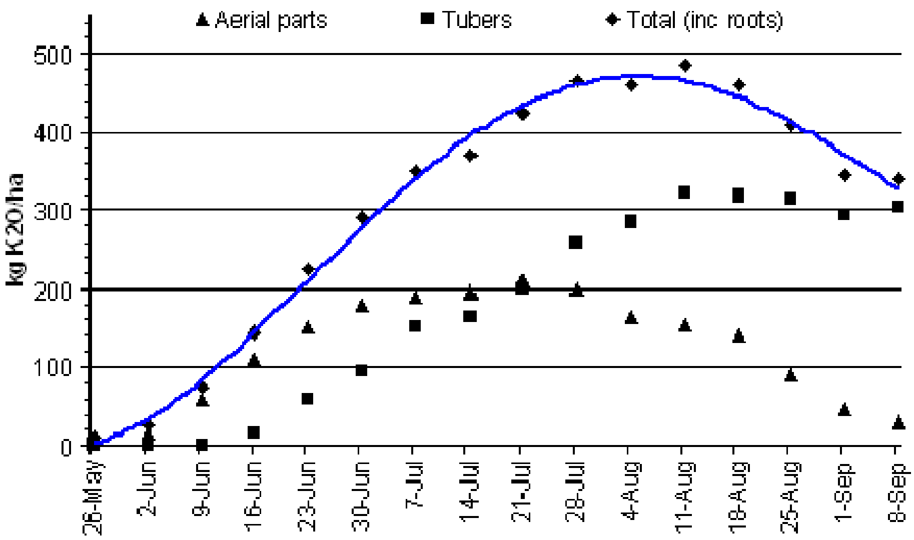


FIGURE 1. TYPICAL POTASH NUTRIENT UPTAKE OF POTATOES DURING THE GROWING SEASON.

Since there is a large potash requirement by the potato crop, and since the cost of potash fertilisers has increased markedly in recent years, it is important to ensure that recommendations to farmers are firmly underpinned by evidence, and that any gaps in information are considered for new research studies.

Note: Conventionally, and in this report, applications to land are expressed as potash (K_2O), but as potassium (K) in crop physiological processes. To convert K to K_2O, multiply by 1.205.

2.1. Project objectives

This review collates and assesses published and other available information on the response of tuber yield to potash application, the removal of potash in potato tubers, and the effect of potassium supply on potato health/quality including the effects on bruising, hollow heart, tuber size, dry matter content, mechanical damage, storage, cooking quality and cooking colour. Proposals are given for future industry-standard recommendations (where there is appropriate robust information), and for future field-based or other research where information gaps are identified.

Data and other robust information has been collected, collated and assessed to derive conclusions to the following issues.

- The role of potassium in potato nutrition.
- The offtake of potash in tubers, and field factors that influence the variation in potash offtake.
- The yield response of potatoes to potash application.
- The supply of potash from different types of livestock manures and composts.
- The impact of potassium supply and potato K content on potato health and quality.
- The impact of different forms of potash fertiliser on yield and quality.
- The impact of soil magnesium supply on potato potassium nutrition.

3. METHODOLOGY

This review is based on existing scientific knowledge concerning the potassium requirements of potatoes during crop production and storage/processing. Proposals for industry standard recommendations for potash use are given that might be adopted with confidence by growers. Gaps in information have been identified and recommendations given for future studies.

The work has been carried out as a desk study by ADAS and SAC. Information has been obtained from existing studies held by the authors, a literature search, and discussions with specialists in the potato production and processing industries, including the Potato Processors Association (PPA).

4. POTASSIUM IN CROP GROWTH

4.1. Potato production and potash use in Britain

4.1.1. Production and markets

The potato crop is an important arable crop throughout Britain. In 2010, there was a total cropped area of 126,400 ha and total production of 6.2 million tonnes (mt). As with many other crops, there has been a trend over many years for a reducing cropped area and gradually increasing yields (Figure 2). In 2009, the average net maincrop yield was 47.6 t/ha, and between 2000-2009, total production fluctuated between 5.4 and 6.7 mt without any clear trend. In the same period, ware prices fluctuated between £69/t (in 2002) and £143/t (in 2007) with an average of £115/t (Potato Council 2010a).

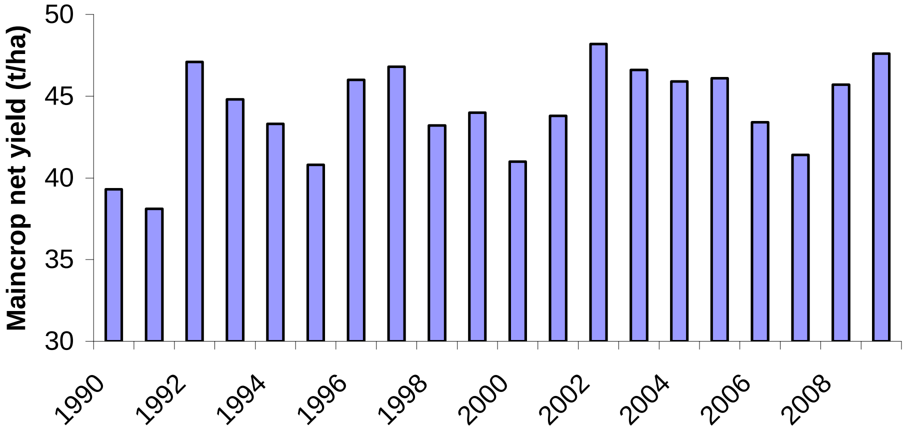


FIGURE 2. YIELD OF MAINCROP POTATOES (T/HA FRESH WT)

Potatoes are grown for a range of different markets. In 2009/10, about 44% of total home-grown production was marketed through the fresh supply chain (2.65 mt), 25% for processing (1.57 mt), 6% for seed (0.38 mt), 24% for stock feed and other losses (1.50 mt), and 1% for a net change in stocks – see Figure 3 (Potato Council 2010b).

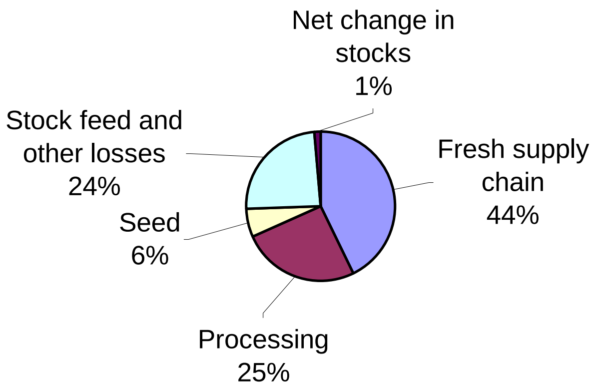


FIGURE 3. MARKETS FOR HOME-GROWN POTATO PRODUCTION

Potatoes grown for processing and their specific quality requirements, is therefore an important sector of the industry, even though in recent years there has been a trend for a small but gradual decrease in the tonnage of potatoes used for processing (Figure 4) – 1.98 mt in 2000 to 1.79 mt in 2009, mostly using home-grown potatoes but with about 5% from imported raw potatoes. In 2009, 55% of potatoes used for processing were marketed as frozen or chilled products, 40% as crisped products and 5% as canned, dehydrated or other products (PCL, 2010b).

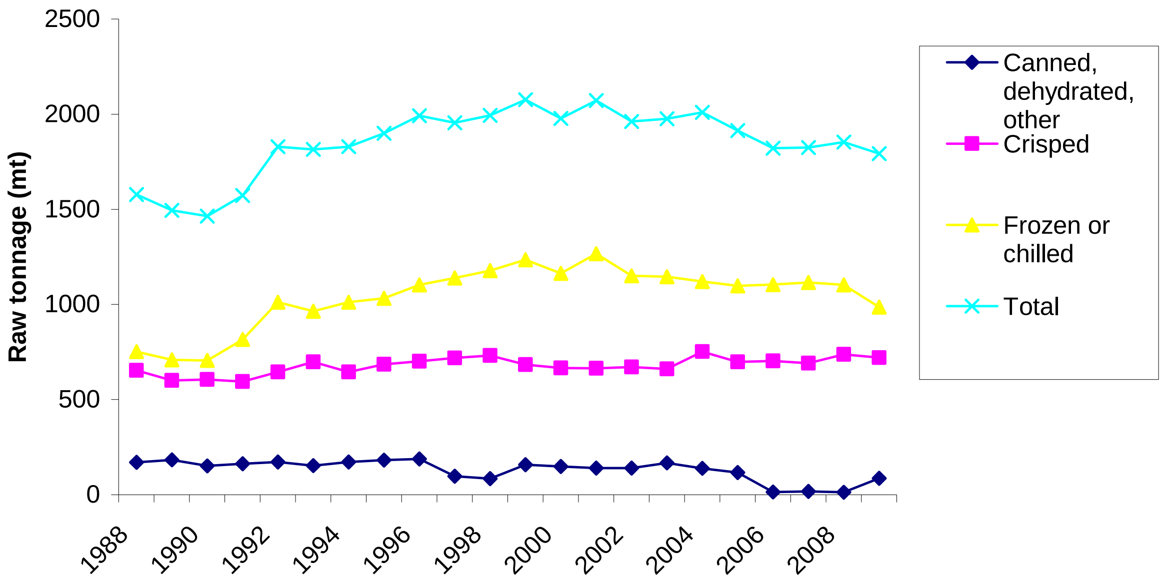


FIGURE 4. POTATOES USED FOR PROCESSING

4.1.2. Fertiliser and organic manure use

Annual fertiliser use statistics are available from the British Survey of Fertiliser Practice (BSFP). Average use of manufactured potash fertiliser to potatoes and other major arable crops between 1990 and 2010 are shown in Figure 5 – these data do not include nutrients applied as organic manure.

Key points to note are as follows:

- Although the average potash fertiliser use for maincrop potatoes is higher than for any other arable crop, the cost represents a small proportion of the total variable costs of growing a typical crop.
- Between 2005 and 2010, the national average potash application rate for maincrop potatoes fluctuated between around 200-250 kg K_2O/ha, and averaged 221 kg K_2O/ha; there was an average of 175 kg K_2O/ha for early/seed crops during this period. In 2010, the average application rate was 204 kg K_2O/ha (maincrop) and 159 kg K_2O/ha (early/seed crops).

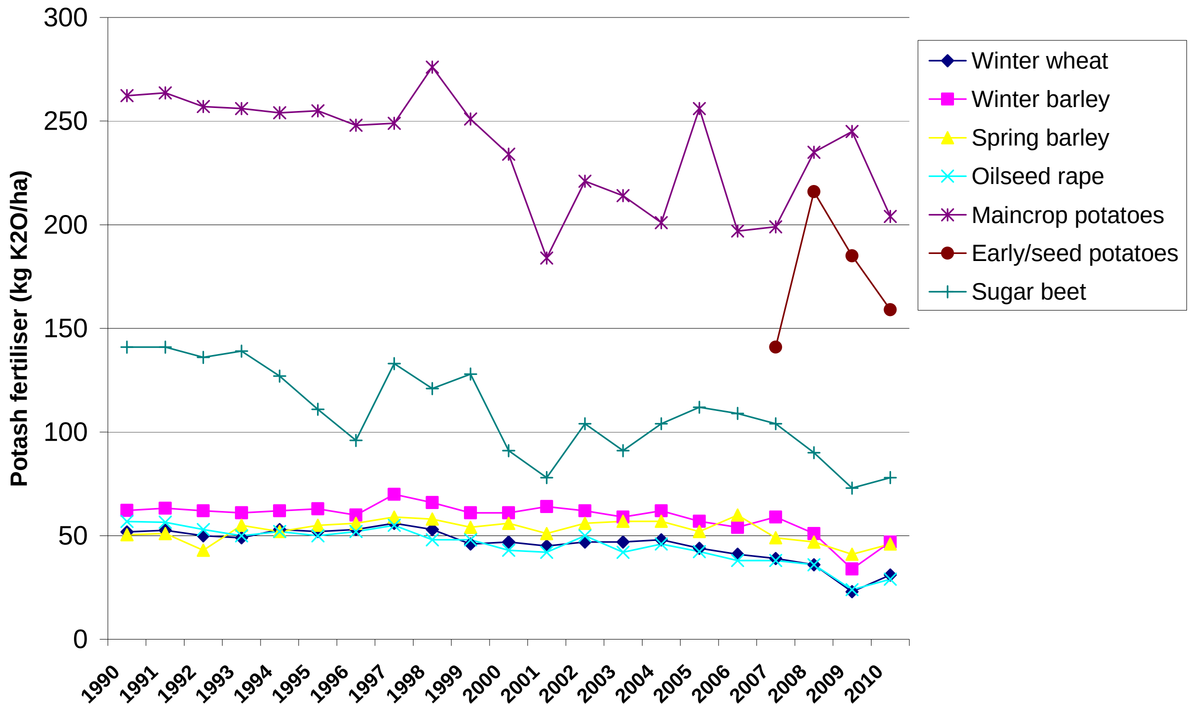


FIGURE 5. TRENDS IN POTASH FERTILISER TO POTATOES AND SOME OTHER ARABLE CROPS

On average over the last 10 years 35% of the maincrop potato crop has received an application of organic manure before planting to improve soil conditions and to provide NPK nutrients (BSFP, 2010). These nutrients are valuable and should be allowed for when deciding on the quantity of manufactured fertiliser to apply. Table 1 shows the nutrients supplied from typical application rates of some common manure types (Defra 2010), and the financial value of these nutrients. It can be seen that large quantities of potash (commonly over 300 kg K_2O/ha) and other nutrients are supplied from a typical application of manure. The potash value alone from a typical application of cattle or pig FYM is currently worth over £150/ha.

TABLE 1. NUTRIENT SUPPLY AND CURRENT FINANCIAL VALUE FROM APPLICATIONS OF SOME FARM MANURES

	Application rate (t/ha)	Crop available N[1]	Total phosphate (P_2O_5)[2]	Total potash (K_2O)	**Total financial value[3]**
		kg/t			**£/ha**
Cattle FYM (old)	40	24	128	320	
		£22	*£114*	*£176*	***312***
Pig FYM (old)	35	25	210	280	
		£23	*£187*	*£154*	***364***
Broiler litter	8	72	200	144	
		£66	*£178*	*£79*	***323***

1. From spring surface applied application.
2. Allow for available manure phosphate (60% of the total content) when calculating the need for phosphate fertiliser. The balance of the total phosphate content should be allowed for when fertilising following crops.
3. Financial value based on ammonium nitrate @ £320/t (92 p/kg), TSP @ £410/t (89p/kg), MoP @ £330/t (55p/kg).

However on average, potato growers do not fully allow for these manure nutrients and tend to over-apply nutrients purchased as manufactured fertiliser. Although based on a limited sample number (c.125 potato fields per year), the annual BSFP provides data on manure use on maincrop potatoes, and an indication of the adjustments that have been made to the amount of manufactured fertiliser used. Table 2 shows BSFP data between 2006 and 2010 for potato crops that did, and did not receive an application of organic manure (BSFP 2010). On average in this period, 35% of the potato area received organic manure, but potash fertiliser use was reduced by only 26 kg/ha. This is less than 10% of a typical application of either cattle or pig FYM which will supply around 300 kg/ha of potash. It has to be concluded therefore, that there is considerable scope for potato growers to more fully allow for the nutrients supplied in organic manure applications unless the manure K inputs applied for the potato crop are allowed for at other points in the rotation.

TABLE 2. AVERAGE APPLICATION RATE OF FERTILISER NUTRIENTS (KG/HA) ON FIELDS THAT DID AND DID NOT RECEIVE AN APPLICATION OF ORGANIC MANURE FOR POTATO CROPPING.

	Nitrogen (N)		Phosphate (P_2O_5)		Potash (K_2O)	
	With manure	No manure	With manure	No manure	With manure	No manure
2010	100	100	75	96	83	94
2009	148	186	136	152	144	154
2008	154	156	140	127	260	227
2007	109	144	91	151	141	230
2006	136	152	90	156	174	225
Mean	129	148	106	136	160	186

4.1.3. Potash recommendations

Current standard recommendations for the use of potash for potato crop production were revised in 2010 and are given in the Fertiliser Manual (RB209) (Defra 2010) and SAC Technical Note TN633 (Sinclair *et al.,* 2010), following a wide ranging review of scientific evidence and consultation within the industry.

Fertiliser Manual (RB209)

The recommendations in the Fertiliser Manual (RB209) at soil Index 2- and 2+ are set to replace the removal of potash in tubers from a crop yielding 50 t/ha using a potash content of 5.8 kg K_2O/t tubers (Table 3). The quantity of potash needed to increase, maintain or reduce the soil Index based on the offtake of potash in tubers, is considered to be greater than the amount needed for maximum yield or quality. Adjustments for lower Indices are based on the standard adjustment of 30 kg K_2O/ha per Index used for all crop types in RB209. There is a nil recommendation at soil K Index 4 or over. Advice is given to adjust potash use for higher or lower yielding crops using the standard offtake figure of 5.8 kg K_2O/t tubers.

There is a recommendation that a small reduction may be appropriate for placed fertiliser though there is considerable uncertainty in this recommendation due to lack of research data. Similarly, a lack of research data has resulted in the same recommendation being given for both bed and ridge and furrow systems. Sulphate of potash (K_2SO_4) rather than muriate of potash (KCl) is recommended if there is a need to increase the tuber dry matter content.

TABLE 3. FERTILISER MANUAL (RB209) RECOMMENDATIONS FOR POTASH USE (KG K_2O/HA) FOR POTATOES

	Index 0	Index 1	Index 2	Index 3	Index 4 and over
All potatoes (50 t/ha yield)	360	330	300	150	0

Notes:

1. Adjust for expected yield using 5.8 kg K_2O/t yield.
2. Large amounts of potash can sometimes reduce tuber dry matter content. Use of sulphate of potash can result in higher dry matter content.
3. If fertiliser is placed, consider a small reduction in the recommended rate.
4. Use same rate for both bed and ridge and furrow systems.

SAC TN633

The SAC recommendations for potatoes grown in Scotland only take account of the possible response of potato yield and quality to potash. Because of concerns about tuber quality (see note below table 4), the recommended rate to be applied before planting does not take account of the potash removed in tubers. However, it is recommended that a balance should be kept between the amount of potash offtake and potash applied, with any imbalance corrected after the potato crop has been harvested when the actual yield is known. The potash offtake is estimated using the same typical value of 5.8 kg K_2O/t fresh tubers that is used in the Fertiliser Manual (RB209).

TABLE 4. SAC RECOMMENDATIONS FOR POTASH USE (KG K_2O/HA) FOR POTATOES

	Very low (VL)	Low (L)	Moderate (M)	High (H)	Very high (VH)
<60 days (seed and punnets) and 60-90 days (seed)	200	160	110	60	0
60-90 days and >90 days (ware)	240	200	150	100	0

Notes:

Fertiliser K increases the susceptibility of potatoes to cracking, splitting and scuffing. The recommended rates should only be exceeded if internal bruising is a more persistent problem than external damage. Higher dry matter tubers are more prone to internal bruising. Soft rots are more prevalent in low dry matter and/or damaged tubers. Therefore K rates above those recommended should be avoided.

Other recommendations

Some processor companies also give potash recommendations to growers. Full details have not been made available to the project team, but it is understood that the recommended rates are substantially higher than those in standard recommendations (Defra, 2010; SAC, 2010).

4.1.4. Soil analysis data

England and Wales

Soil analysis data collated by the Professional Agricultural Analysis Group (PAAG 2010) from around 200,000 samples analysis by commercial laboratories in 2009/10 gives a good indication of the distribution of soil Indices in agricultural soils in England and Wales, though the dataset is not random and may be biased to well managed soils. Figure 6 shows the distribution of soil K and soil Mg Indices in arable land. About one-third of samples are at the optimum soil K Index 2- and soil Mg Index 2. The remaining samples are either at lower (deficient) indices or higher (surplus) Indices.

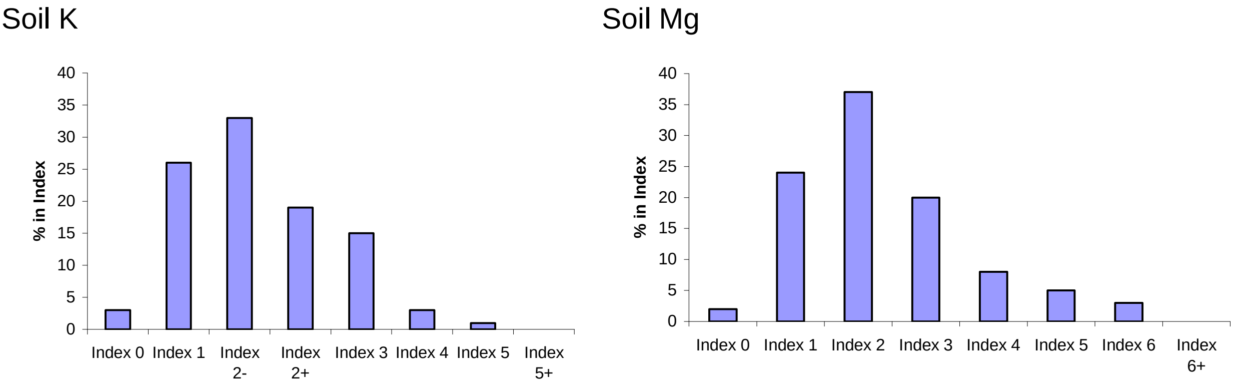


FIGURE 6. DISTRIBUTION OF SOIL K AND MG INDICES ON ARABLE LAND IN ENGLAND AND WALES IN 2009/10

These data do not indicate the distribution of soil Indices on potato growing land. However, Skinner and Todd (1998) analysed data from the Representative Soil Sampling Survey (RSSS) between 1988-93 and found that soil K Indices were generally lower on potato growing land than land used for other arable crops. This would reflect that potatoes are usually grown on light and medium textured soils that have a naturally lower potassium content than heavier soils that often have a higher content of natural potassium-rich clay. In this dataset of 56 samples on potato growing land, 50% of samples were at K Index 2, 36% were below Index 2 (probably mostly at Index 1) and only 14% were above Index 2. Thus, a significant proportion of potato growing land in England and Wales is likely to be at soil K Index 1 where potash application can result in yield increases.

Scotland

The results of soil analysis on c.130,000 samples taken between 1996 to 2010 have been assessed. A significant proportion of the samples have agronomic information relating to the previous and next crop. These key management variables have been used to identify the significance of cropping system, including potatoes, on soil K and Mg status. SAC classify extractable soil K and Mg values into 6 categories (5 for Mg) ranging from very low (VL) to very high (VH) as shown in Table 5 (Sinclair *et al*., 2010), although the same potash recommendation for potatoes is given at soil K status M+ and M-.

TABLE 5. CLASSIFICATION OF MG/L VALUES INTO SAC STATUS FOR EXTRACTABLE SOIL K AND MG

SAC Status	K (mg/l)	Mg (mg/l)
VL	0 – 39	0 – 19
L	40 – 75	20 – 60
M-	76 – 140	61 – 200
M+	141 – 200	61 – 200
H	201 – 400	201 – 1000
VH	>400	>1000

The data have been summarised and interpreted for the Scottish sub-regions that are used in Scottish Government Census data reports. The distribution of soil K and Mg status by Scottish sub-region are shown in Figures 7 and 8. The main potato growing areas are Tayside (15% of national potato area), Fife (12%), Lothian (8%), NE Scotland (7%) and Scottish Borders (6%). In these areas, more than 80% of all soil samples are at the target K Moderate (M) status or above. The percentages of all samples at a high soil Mg status are 46%, 41%, 13% and 35% for Tayside, Fife, Lothian and NE Scotland respectively. The greater percentage of samples in the high Mg status in Tayside and Fife reflect the use of magnesian limestone from Durham.

Extractable K and Mg level of soil collected before (5,604 samples) and following (1,568 samples) potato cropping are shown in Figure 9. Annual mean values of extractable K were above 141 mg/l (lowest point of M+ status) in 12 years out of 15 in samples taken immediately before potatoes, and in 14 years out of 15 in samples taken following potatoes. There is no evidence from this dataset to indicate that extractable soil K is either significantly lower following potatoes, or has built up during the rotation before planting potatoes.

Annual mean values of extractable Mg were above 150 mg/l in 10 years out of 15 in samples taken immediately before potatoes, and in 6 years out of 15 in samples taken following potatoes.

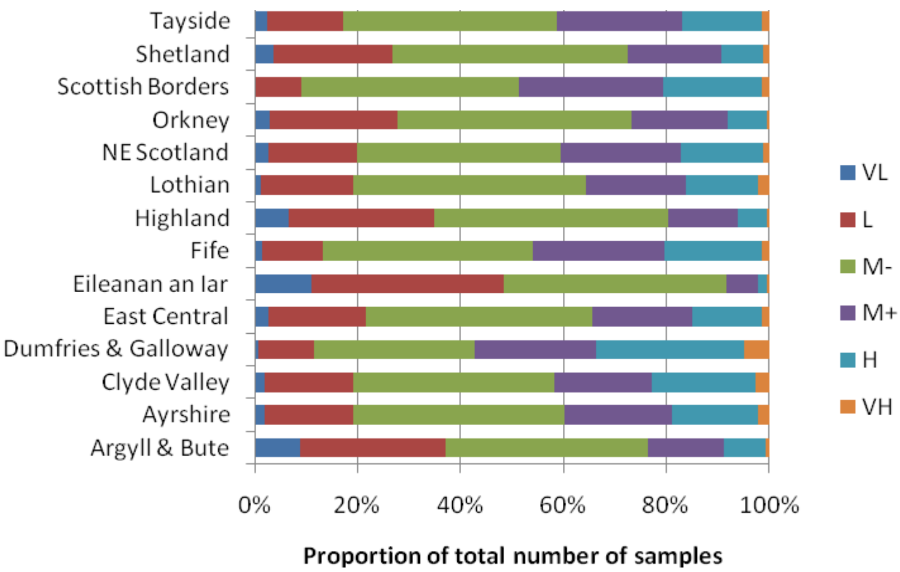


FIGURE 7. SOIL K STATUS SUMMARISED BY SCOTTISH SUB- REGION

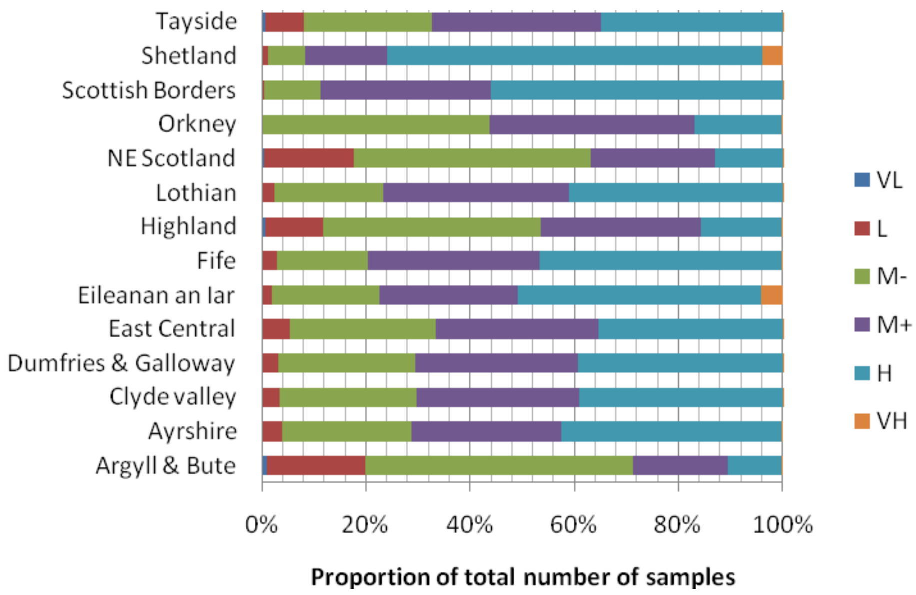
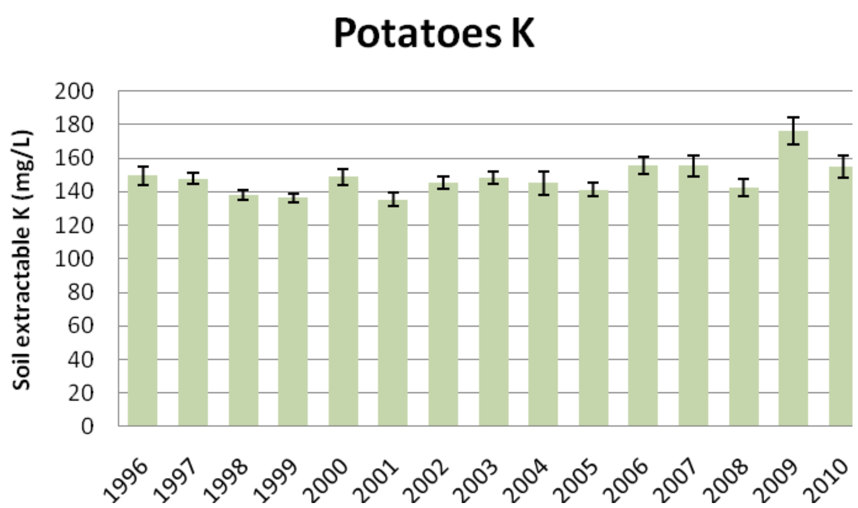


FIGURE 8. SOIL MG STATUS SUMMARISED BY SCOTTISH SUB- REGION



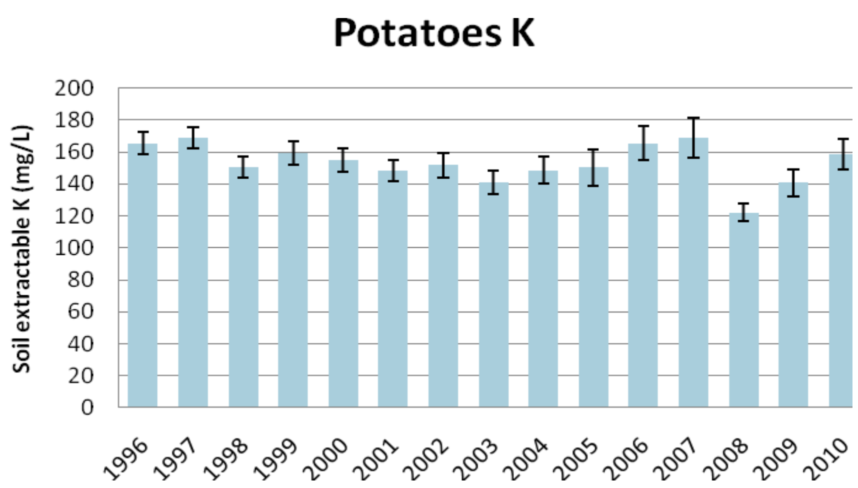


FIGURE 9. EXTRACTABLE SOIL K IN SAMPLES TAKEN IMMEDIATELY BEFORE POTATO CROPPING (TOP CHART) AND FOLLOWING POTATO CROPPING (BOTTOM CHART) – ERROR BARS SHOW THE STANDARD ERROR OF THE MEAN

Antagonism between potassium and magnesium

Potassium and magnesium are both essential for crop growth but a high supply of one in the soil can inhibit uptake of the other, potentially causing an induced deficiency which is likely to be more common in un-irrigated crops under dry conditions. In practice, imbalances are rare, and induced magnesium deficiency due to high potassium is more likely than induced potassium deficiency due to high magnesium. However, investigation of potato growth problems by ADAS has, on occasions over many years, identified potassium deficiency with strong suggestions that the deficiency may have been wholly or partly induced by high soil Mg levels, where the ratio of soil K:Mg (as mg/l) was below 0.5:1. Such high soil Mg levels are caused by regular use of magnesian limestone as the source of agricultural lime.

Since potatoes are grown on sandy and medium textured soils which are commonly naturally acid, lime is usually applied during rotations that include potatoes, though usually not immediately in front of potatoes because of the risk of common scab. Where the local source of lime is magnesian limestone, it is known that regular applications over many years can result in a build up of soil Mg Indices to unnecessarily high levels. Magnesian limestone formations and associated lime quarries occur through Co Durham, Yorkshire and Nottinghamshire. Since agricultural lime produced from magnesian limestone contains about 10-12% Mg, a typical application of 5 t/ha lime will supply over 500 kg/ha Mg, equivalent to c.100 kg/ha Mg per year from a typical lime application frequency of once every 5 years. This is well above the typical crop offtake of less than 20 kg/ha for most crops. Allison (2000) found that the average removal of magnesium in potato tubers was 12 kg Mg/ha. Magnesium does not leach from soils to any extent so any surplus application of Mg will accumulate in the soil, raising soil Mg levels and the risk of induced potassium deficiency.

Dampney (1994) analysed soil sample results from the Representative Soil Sampling Survey (RSSS) carried out in England and Wales, and found that in Cleveland, South Yorkshire and West Yorkshire, over 50% of samples were at soil Mg Index 5 or over and a soil K:Mg ratio (based on soil mg/l) below 0.5:1. The recommended maintenance level for soil Mg is Index 2 (Defra 2010). In several other counties close to supplies of magnesian limestone (e.g. Gloucestershire, Nottinghamshire, Tyne&Wear, Warwickshire, Worcestershire), over 25% of samples were at soil Mg Index 5 or over and a soil K:Mg ratio below 0.5:1. Dampney (1994) reported that based on the RSSS data and MAFF census data, the total area of crops in England and Wales with a K:Mg ratio below 0.5:1 might be around 410,000 ha of which about 240,000 ha (48%) is in the Northern counties, Yorkshire and Nottinghamshire, and around 18,000 ha of potatoes (c.13% of the national area). In addition, it is known that magnesian lime is used as the main liming material in parts of Scotland and where similar concerns exist – a high soil Mg status is common in most Scottish regions (Figure 8).

There is limited research work on the potash requirements of potatoes grown at high soil Mg Indices (Index 5 or over), but it is reasonable to expect that these crops may have a higher potash requirement, or be more at risk to yield or quality losses due to shortages of potassium. Allison *et al* (2001) reported results for 3 sites at Mg Index 5 though one of these sites had a high soil K as well as high soil Mg Index so does not represent the low soil K: high soil Mg situation (i.e. below 0.5:1 ratio). There were 5 sites with a soil K:Mg ration below 0.5:1 and at 4 of these sites a significant yield response to potash application was reported. However, it is not possible to say if the

Mg factor made the difference in responsiveness, even though other sites with similar soil K did not respond to potash application. If a soil K:Mg ratio of 0.5:1 is substantiated as a critical point, then there are significant areas of farmed land where high magnesium inputs from liming may be creating nutrient imbalances and potentially increasing the need for potash application. From basic principles, it is possible that the level of soil Mg might influence the nutrient removal of potassium in tubers, with a high soil Mg Index resulting in a lower removal of potash per tonne of tubers. However, there is no data to test if this relationship exists.

4.2. Potash offtake in tubers

The basis of good nutrient management practice for potash (and phosphate) for all crops, is that nutrients should be applied that will either result in an increase in the yield or quality of the crop grown (i.e. the crop is 'responsive') or that will build up, maintain or run down the soil nutrient Index, depending if this is low, satisfactory or high according to soil analysis. The satisfactory 'target' soil K Index for potatoes in England, Wales and Northern Ireland is 2 (120-240 mg/l) (Defra 2010) and soil K status M in Scotland (Sinclair *et al.,* 2010). Standard nutrient removal values are quoted for most crops and these are used to calculate the amount of nutrient needed to replace the nutrients removed from the field in crop produce.

Various authors have reported data on the removal of potash in maincrop potato tubers. The source data summarised in Table 6 includes those data which provided the basis for the current standard recommendations used in England and Wales, and in Scotland. Sample details for each set of raw data are shown where these are available. Using available data summarised in Table 6, the 7th (Defra 2000) and 8th edition of RB209, and current SAC recommendations have set a potash offtake standard for potato tubers of 5.8 kg K_2O/t fresh tuber (Defra 2010; Sinclair *et al.,* 2010 2010).

TABLE 6. DATA SOURCES FOR REMOVAL OF POTASH IN POTATO TUBERS.

Source	Samples	Variety	Potash content kg K_2O/t
ADAS, 1979			5.9
Allison *et al.,* 2000	13 experiments	Mixed	5.2
Allison *et al.*, 2001	33 experiments	Mixed	5.1 (range 2.8-5.7)
Anderson and Hewgill, 1978			5.8
Burton, 1996			6.0
Duengeverordnung, 1996			6.0
Gunasema, 1969			5.5
DGER/SCPA, France, 1993			6.0
Kunkel *et al.,* 1973 (USA)			4.7
Loué, 1977	23 experiments		5.3
Russell, 1973			5.7
SAC, 1996	24 seed stocks	Mixed	6.1
Widdowson and Penny, 1975	4 experiments	Pentland Crown, Record, King Edward	6.1-6.2
		Range Mean (not weighted)	4.7-6.2 5.6

There are few studies that have examined the field factors that might influence the variability in the removal of potash in tubers. Gunasema reported that potash removal varied between 4.5-6.5 kg K_2O/t tubers, and was inversely related to tuber yield (though with yield levels not exceeding 23 t/ha). Allison *et al.* (2000) indicated that the variability in removal could not be explained by the soil K Index (Figure 10). Intuitively, both of these relationships would be expected. Attempts to understand the causes of variability in potash offtake in cereal straw (Withers, 1991) found that the variation could only partly be explained by soil K Index, and multiple correlation with other site variables could not improve the relationship.

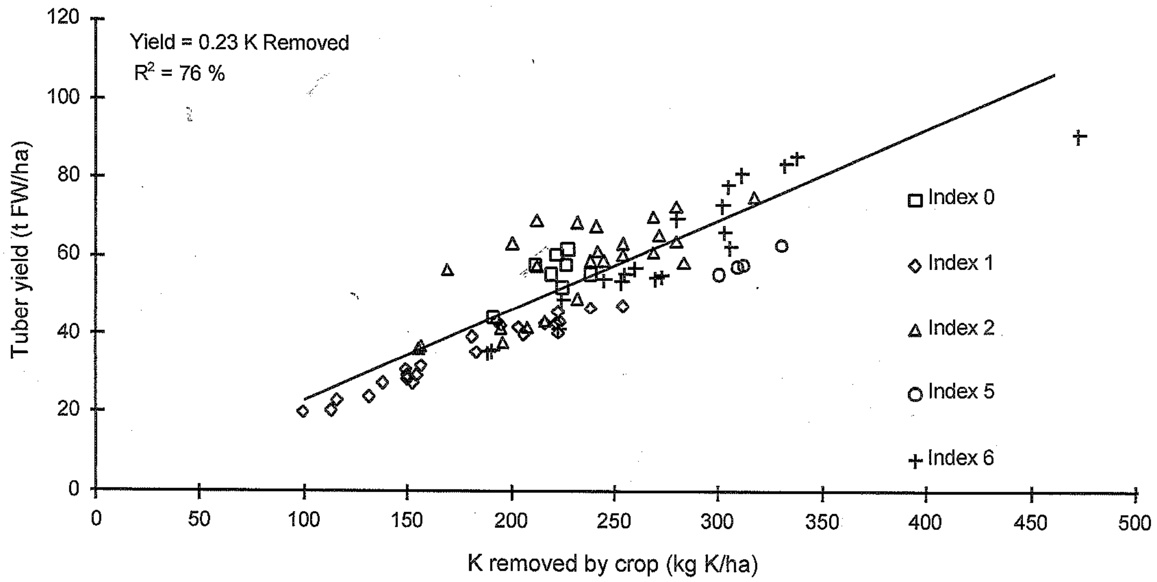


FIGURE 10. RELATIONSHIP BETWEEN TUBER YIELD AND POTASSIUM (K) REMOVAL IN 13 EXPERIMENTS 1994-1999 FOR DIFFERENT SOIL K INDICES - EACH POINT IS A TREATMENT MEAN; K_2O = K X 1.205 (FROM ALLISON *ET AL.*, 2000).

4.3. Tuber yield responses

Since large quantities of potash (typically 290 kg K_2O/ha for 50 t/ha tubers) are removed in potatoes (as discussed in section 4.2), larger applications will only be justified if yield and/or quality improvements are likely from higher rates of application of potash – i.e. if the potash need for 'response' of potato yield and/or quality is greater than the need to replace the potash removed in tubers. Although this is the technical correct approach to potash use for potatoes, it is recognised that many potato crops are grown on short-term rented land where the potato grower may have less interest in maintaining the long term potassium fertility of the soil than the land owner. This arrangement should not alter the best practice for potassium nutrition whether practised by the potato grower or land owner, though the potato grower may be keener to limit the potash application rate to that which is needed to optimise yield and quality alone.

Various experiments have been carried out in Britain studying the tuber yield response of potatoes to application of potash fertiliser. The nature and conclusions of these studies are summarised as follows. Although these data are informative and provide a large part of the evidence underpinning current industry standard recommendations, most studies were carried out over 40 years ago when potato growing systems, varieties and tuber yields were different to those found today. The results of these older experiments must therefore be treated with caution. As a general conclusion, tuber yield responses were small or absent if the soil K Index was Index 2+ (180 mg/l) or over. There is no evidence of tuber yield responses to potash applied at rates higher than needed to replace the potash removed in tubers.

Boyd and Dermott (1961)

These authors summarised the results of 124 experiments carried out in England between 1955-1961. The average tuber yield response was 2.4 t/ha from an application of 94 kg K_2O/ha but only a further 0.6 t/ha from double this application rate (i.e. 188 kg/ha). The average tuber fresh weight yield was only 25 t/ha.

Eagle (1967)

Eagle analysed data from 71 potato experiments on 9 widely differing soil types. He found a weak correlation (-0.23) between soil exchangeable K (used to determine the soil K Index) and the magnitude of tuber yield response to applied potash (Figure 11 taken from Allison *et al,* 2001). Large yield responses occurred at Index 0 and 1 but were small or absent at K Index 2 or over.

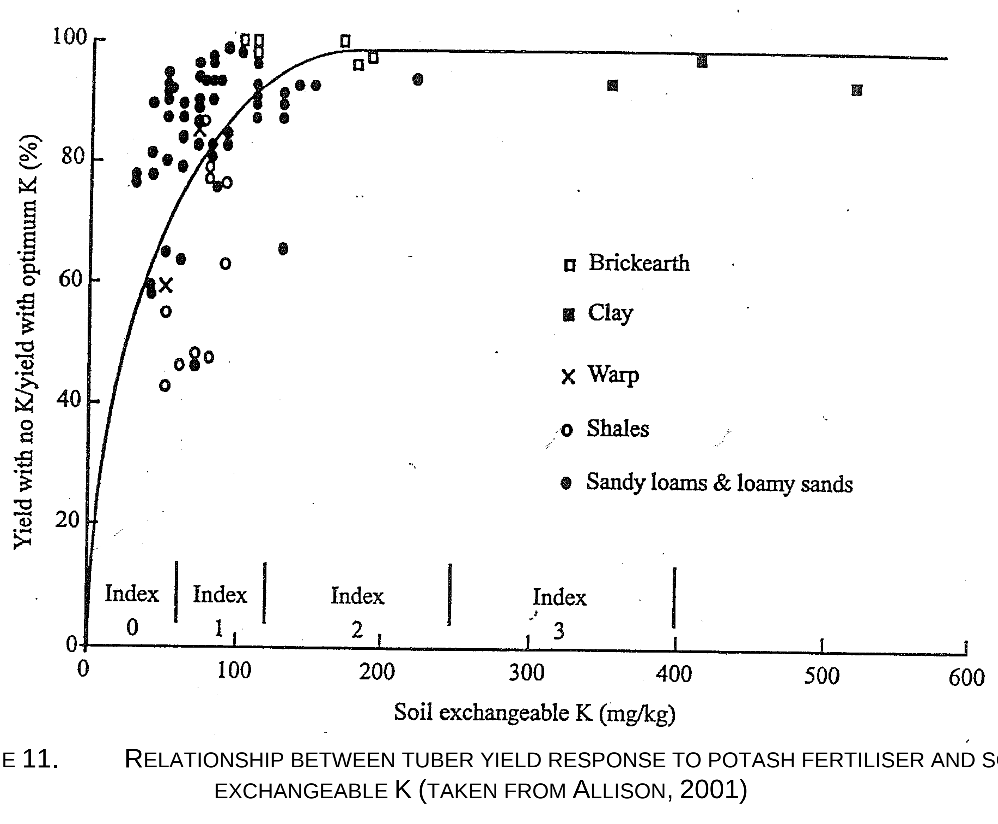


FIGURE 11. RELATIONSHIP BETWEEN TUBER YIELD RESPONSE TO POTASH FERTILISER AND SOIL EXCHANGEABLE K (TAKEN FROM ALLISON, 2001)

Birch *et al.* (1967)
In 51 experiments across Britain, these authors tested the response of potatoes to 4 rates of potash application (up to 270 kg K_2O/ha) using the variety Majestic. Yield responses ranging from <0.5 t/ha up to c.10 t/ha were recorded, with the size of the yield increase and the optimum potash rate both related to the soil K level. Since the soil analysis extractant used in this study was citric acid (which cannot be directly compared with ammonium nitrate, the standard soil extractant used today), it is not possible to interpret these data in terms of potash responses at different soil K Indices.

ADAS field experiments (1966-1972)
A total of 58 field experiments were carried out in 3 potato growing areas to study the response of tuber yields to factorial combinations of different rates of nitrogen, phosphate and potash.

- At 16 experiments on sandy soils in the Vale of Eden, Cumbria, testing 3 rates of potash, Archer *et al* (1976) reported an average increase of 7 t/ha ware production from potash application (yield increase from 29 to 36 t/ha), with an optimum rate around 250 kg K_2O/ha. The initial response was related to the amount of soil K.
- At a further 16 experiments on deep sandy loam soils in Herefordshire (Ross soil series, Farrar and Boyd (1976) reported only small responses to potash application. At soil K Index 0 or 1 (7 sites), the average yield response to 113 kg K_2O/ha was 2.8 t/ha with a small extra yield increase to twice this rate; at Index 2 (7 sites), the average yield increase was 0.8 t/ha with no yield increase at one site at soil K Index 4.
- At 26 experiments testing 3 rates of potash application on magnesian limestone soils in Yorkshire, Webber *et al.*, (1976) reported generally low yield responses to potash except on light textured soils at soil K Index 0 or 1. At experiments with less than 150 mg/l extractable K (middle of Index 2-), there was an average tuber yield response of c.1.3 t/ha to each increment of 100 kg K_2O/ha up to 300 kg/ha. There was no response to potash at experiments with more than 180 mg/l extractable K (Index 2+ or over).
- At 32 experiments on warp soils in N and S Humberside carried out between 1972-1977, Johnson and Zemroch (1980) reported that there were small and linear responses at 8 sites. Optimum potash rates were not determined.

International Potash Institute (IPI)
Perrenoud (1993) summarised international evidence for fertilising high yielding potatoes, including evidence from both developed and developing countries. The review included some but not all of the available evidence from Britain. The relevant conclusion for this review was that potash application commonly increased tuber yields.

Allison *et al.* (2001)
33 field experiments were carried out between 1989 and 1999 testing potash rates of 0, 85, 170, 250 and 320 kg K_2O/ha on variety Estima. These are the most recent experiments that have been carried out and reflect modern growing practices and crop outputs. The average tuber yield was 48 t/ha which is the same as today's national average yield. Statistically significant yield responses to potash application were only obtained at 7 of the 33 experiments based on significance testing between each incremental rate of applied potash. Optimum potash application rates ranged between

c.105 and 250 kg K_2O/ha – even the highest optimum rate was less than the amount of potash removed in the tubers. Compared with treatments that received no potash application, the tuber yield response ranged from 4 t/ha up to 21 t/ha at an experiment with a soil K Index of 0 (very deficient). The authors concluded that soil analysis for exchangeable K was a poor indicator of tuber yield response to potash application – 1 of 4 experiments at soil K Index 0 gave a tuber yield response to potash, 4 of 11 experiments at Index 1, none of 10 experiments at Index 2, 1 of 3 experiments at Index 3, and 1 of 4 experiments at Index 4 or over.

ADAS Gleadthorpe (2002)
In 2002, the response of 8 varieties to nil and 325 kg K_2O/ha of potash (4 replicates per treatment) was tested on a loamy sand soil at ADAS Gleadthorpe. Soil analysis showed the soil to have 79 mg/l K (soil K Index 1). All varieties gave a tuber yield response to potash with an average yield increase of 12 t/ha (from 67.2 to 79.2 t/ha). The optimum potash rate could not be determined from this experiment. Based on the standard potash removal of 5.8 kg K_20/t, the maximum average yield is equivalent to a removal of 460 kg K_2O/ha.

5. POTASSIUM AND TUBER QUALITY

5.1. Bruising (blackspot)

Black spot is caused by oxidation of phenolic compounds (such as tyrosine and chlorogenic acid) to melanin by polyphenoloxidase (PPO) after bruising. A critical review of many factors affecting bruising was carried out by McGarry *et al.* (1966). They confirm that there are many reports of a reduction in bruising by increasing potassium application (Oortwijn Botjes & Verhoeven, 1927; Kunkel and Gardner, 1965; Prummel, 1973; Prummel, 1986; Chapman *et al*., 1992; Winkelmann, 1992, Maier *et al*., 1986) but there was considerable variability in aspects of methodology such as how damage was inflicted and method of assessment. Some studies have shown no effect of potassium on bruising, or effects only on potassium deficient soils (Dwelle *et al*., 1975 & 1977). Prummel (1986), reviewing a series of trials, considered that higher rates of potassium than are usually required for maximum yield are necessary to prevent bruising. Others concur with this view (e.g. Maier *et al*., 1986; Wegener, 1979). McGarry *et al*. (1996) concluded that there was sufficient evidence to indicate that potassium nutrition plays a role in the bruising response. However, they support the contention by Scudder *et al*. (1950) and Maier *et al*. (1986) that there would seem to be little to commend the use of excessive rates of fertiliser application to achieve a reduction in the incidence of internal damage even on potassium-deficient soils, since the benefit obtained would be too small to be of practical value. They suggest that application at rates for maximum yield is adequate.

Any effect of potassium is thought to be mediated through its effects on starch content (thus dry matter), cell turgor and organic acid concentration. It is considered that in some cultivars, blackspot susceptibility is linked to reduced dry matter content (Kunkel & Gardner, 1965; Murphy & Goven, 1966). One view has been that with increasing potassium, dry matter content decreases, and potassium and tyrosine contents of the dry matter are increased (Jacob, 1959). McGarry *et al*. (1996) emphasise that the water status of tubers may have a major role to play in susceptibility to bruising. There are also large differences in susceptibility to black spot between cultivars. Vertregt (1968) found differences in black spot susceptibility between cultivars unrelated to tyrosine content or phenoloxidase activity. Great variability in susceptibility in blackspot occurs within a tuber and between tubers (Kunkel *et al*., 1986).

Cultivars with different susceptibility to black spot were found to have different potassium and dry matter contents. Winkelmann (1992) determined that the optimal potassium content of the dry matter of potatoes (including for reduction of blackspot) was 2.2-2.5%. Prummel (1991) concurred that 2.2% was a critical value to reduce bruising (as well as no more than 20% dry matter). Vertregt (1968) showed that on silt soils in the Netherlands, with unlimited potassium the content in tubers was around 650 meq (25.4 g/kg dry matter) and black spot was negligible where this content was exceeded. However, since the potassium content of tubers is negatively correlated with dry matter content, McGarry *et al*. (1966) suggest that potassium effects on bruising may be explained more by the dry matter content than the potassium content. The impact of potassium may be through the water status of the plant, but the relationship with other components of the bruising syndrome such as PPO and free tyrosine cannot be ignored.

Van Loon and Van den Berg (2003/4) carrying out trials on two contrasting soil types, showed a reduction in blackspot susceptibility in one of two varieties as the dose of potassium chloride increased from 0 to 400 kg/ha. Although the timing of potassium application is not clear from their study, it would appear to have been at planting since the initial growth of the crop and stem numbers were significantly affected by chloride fertilisation. With a variety exhibiting low susceptibility to blackspot (Bintje), there was no effect of potassium chloride fertilisation. However, in a blackspot susceptible variety (Marijke) chloride fertilisation significantly reduced blackspot. This effect was greater on heavy clay soil. Where growers using potassium chloride apply it 4 or more weeks before planting, the impact of chloride ions on crop growth and effects on tuber quality as reported in most literature cited here, would be largely irrelevant. Maier *et al*. (1986) has also demonstrated that potassium chloride was more effective than potassium sulphate at reducing blackspot susceptibility.

At the EAPR (European Association for Potato Research) conference in Finland in late July 2011, Belgium researchers reported a series of trials where potash was applied in various forms before planting and two months after planting. The quantity of pre-planting potash applied matched local recommendations and only small yield responses were recorded. Black spot was reduced by the pre-planting applications and further reduced by the post-planting applications, especially potassium chloride. There was also a small reduction of dry matter from the post-planting potash. This late application of potash has not been tested elsewhere and may be a technique that would usefully be tested in Britain.

5.2. Dry matter (specific gravity)

Specific gravity is the relative weight of potatoes compared to the weight of the same volume of water. It is closely related to the tuber starch content or total solids and thus dry matter content of tubers. The terms 'specific gravity' and 'dry matter content', as one measure of potato quality, may be used interchangeably (Stark & Love, 2003).

Laboski & Kelling (2007) recently reviewed the effect of fertiliser management practice on tuber specific gravity, though their review was strongly biased to North American studies. However, their conclusions accord with European data. There are numerous reports of reductions in specific gravity or percentage dry matter with increasing applications of potash fertiliser (Terman *et al*., 1953; Dickins *et al*., 1962; Timm & Merkle, 1963; Kunkel & Gardner, 1965; Murphy & Goven, 1966; Chamberland & Scott, 1968; Sandstra *et al*., 1968; Kunkel & Holstad, 1972; White *et al*., 1974; Dubetz & Bole, 1975; McDole, 1978; McDole *et al*., 1978; Roberts & Beaton, 1988; Maier *et al*., 1994; Westermann *et al*., 1994; Panique *et al*., 1997; Haberland, 2006). In some instances, reductions in dry matter content occurred only where high rates of potash were applied (e.g. Panique *et al*., 1997) or where soil reserves of potassium were excessive (e.g. Murphy & Goven, 1959; Kunkel & Holstad, 1972; Redulla *et al*., 2002).

A few researchers have recorded increases in dry matter content with increasing applied potash (Peterson *et al*., 1971; Maier *et al*., 1986; Chapman *et al*., 1992; McNabnay *et al*., 1999), but these occurred on potassium deficient soils and usually only up to the rate required for optimum yield. The relationship between increase in dry matter content of tubers in potassium deficient soils, or decrease where sufficient soil potassium is present, has been re-enforced by Maier *et al*. (1994).

Potassium chloride fertilisers have been shown to result in a greater reduction in tuber dry matter concentration when compared to potassium sulphate or nitrate, but the effect is not completely consistent. The majority of studies have shown reductions, sometimes significant, where potassium chloride was used (Wilcox, 1961; Laughlin, 1962a; Timm & Merkle, 1963; Murphy & Goven, 1966; McDole, 1978; Panique *et al*., 1997; Silva *et al*., 1989; Van Loon & Van den Berg, 2003/4; Craighead & Martin, 2002/3). Van Loon and Van den Berg, for example found significant reductions in tuber dry matter concentrations of 0.6-1.1%. However, Timm & Merkle (1963) found the effect in rain-fed potatoes in only one of two varieties, and Panique *et al*. (1997) only found the effect in 3 out of 11 trials. Other researchers (Stanley & Jewell, 1989; Westermann *et al*., 1994; Davenport & Bentley, 2001) have found no increased effect of chloride on tuber specific gravity, though their trials were all irrigated. Van Loon & Van den Berg (2003/4) concluded that a good water supply is an important factor in preventing reductions in dry matter content as a result of chloride fertilisation.

The format of trials reported vary greatly, some comparing just one potash rate, as chloride or sulphate compared with no potash, rather than a range of potash rates. In almost all the trials reporting on the effect of potassium chloride on specific gravity, the fertiliser was applied at planting and, depending on circumstances (notably irrigation), this may have affected uptake of chloride ions. In the UK, muriate of potash (potassium chloride) is generally applied several to many weeks prior to planting and any effects from chloride ions will be minimised. Thus it is unclear whether under current UK practice the use of potassium chloride would have any additional effect on specific gravity at all. Where small changes in specific gravity or dry matter content are being evaluated, low coefficients of variation (CV) would be required to detect a significant difference.

In unpublished trial data from McCain (UK) between 2002-2005 (Blades, R; personal communication) comparing 0, 375 and 450 kg/ha potash on 4 processing varieties (Pentland Dell, Russet Burbank, Shepody and Umatilla Russet), an analysis of results over three years showed consistent reductions in dry matter content following application of 375 and 450 kg/ha potash compared with no potash. The reductions were significant in three varieties. Reductions in dry matter differed between varieties but ranged from 0.7 to 3.1%. There were no significant differences in dry matter content between the 375 and 450 kg/ha rates, but the highest rate was consistently the same or less than that from lower rate (0 to 0.8%).

Specific gravity has not been a good indicator for fry colour (Kunkel & Holstad, 1972).

5.3. Enzymic browning (EB)

Enzymic browning is a well understood process that occurs after preparation for cooking. It results from oxidation of phenolic compounds, especially chlorogenic acid and tyrosine, by phenolase. Oxidation of tyrosine gives dark brown pigments and eventually melanin. Chlorogenic acid is an activator for phenolase. Concentrations of chlorogenic acid and phenolase are not limiting, thus the concentration of tyrosine is most important in controlling EB.

There are cultivar differences in EB but they are mediated by environmental conditions. Thus the amount of EB produced from a certain concentration of tyrosine varies according to environmental factors. Climatic factors are considered more important than edaphic factors but mineral nutrition is known to affect EB.

Several studies have shown that when high levels of K are applied, EB, tyrosine and sometimes phenolase are reduced (Mulder, 1949; Welte & Mulden, 1966; Baerug & Enge, 1974; Mundy & Munsh, 1993). Potassium chloride has proved more effective at reducing EB and tyrosine than potassium sulphate (Hughes and Mapson, 1967). In their review, McGarry *et al*., 1996) considered the effect of potassium on EB was not large, and was mainly observed where soil analysis indicated potassium deficient soils. Furunes (1990) concluded that extra potash over that required for optimum yield was not required.

5.4. Fry colour (Non-enzymic browning)

This summary includes references to fry colour and reducing sugars and considers them equivalent. Unacceptable browning during frying is largely dependent on the amount of reducing sugars present in tubers. Like non-enzymic browning, environmental conditions affect the levels of reducing sugars. Thus acceptable fry colours are more difficult to achieve in potatoes from Northern Britain, or where late irrigation is applied or where crop maturity is delayed in the autumn.

Research to determine the relationship between applied fertiliser and reducing sugars or fry colour are inconclusive. Some researchers have concluded that the effects of increasing potash fertiliser on reducing sugars/fry colour are positive but mostly relatively small (e.g. Wilcox, 1961; Murphy and Goven, 1966; Welte & Mulder, 1966;

Herlihy & Carroll, 1969; Zehler *et al*., 1981; Sharma & Aurora, 1988; Chapman *et al*., 1992; Perrenoud, 1993; Putz, 1994; Kunkel & Halsted, 1972). In studies by Harrison *et al*. (1982), increasing the supply of potash sufficient for maximum yield did not result in further improvement in chip colour. Kunkel & Holstad (1972) showed significant improvements in crisp fry colour with increasing potash, but the results were considered too small for practical significance. In general, the greatest improvements in fry colour, usually significant, came with the first increment of potash. Improvements in fry colour diminished with further increases in potash and these were rarely significant. Others have found no relationship between potash fertiliser and reducing sugars or fry colour (Winkelmann, 1992; Allison *et al*., 2001).

Stanley and Jewel (1989) studying Maris Piper and Pentland Dell on a sandy loam soil type, found the lowest reducing sugars and French fry colour in Maris Piper, except where 300 kg/ha K_2O was applied to Pentland Dell. They concluded that the effect of potassium source was not significant and the effect of rate of potash on reducing sugars and chip colour could not be reliably predicted on the soil type. Westermann (1994) showed that potash application decreased reducing sugars at both ends of the tuber. Kunkel and Holstad (1972) concluded that growers should fertilise for maximum yield even where fry colour was the major concern.

Where improvements in fry colour or reductions in reducing sugars occurred as a result of potash fertilisation, some studies have suggested they occurred irrespective of potash source (Murphy and Goven, 1966; Wilcox, 1961). Others have found potassium chloride more effective. Thus Harrap (1960) found a decrease in reducing sugars as a result of high chloride concentrations, and others have shown that increasing chloride fertilisation has led to a slight but significantly lighter fry colour (Murphy & Goven, 1966; Hojmark, 1977; Veerman, 2001; Van Loon & Van den Berg, 2003/4). Eastwood and Watts (1956) reported that potassium chloride gave a slightly lighter chip colour than potassium sulphate at the same application level. Similarly, Murphy & Govern (1959) found that the sulphate form of potassium produced darker chips.

5.5. After cooking discolouration or blackening (ACD)

Hughes *et al*. (1962a, b, c; 1967) have produced reviews on ACD. ACD originates from oxidation of a ferric-diphenol complex (Juul, 1949). The complex is formed by chlorogenic acid (Kiermeier & Rickerl, 1955) and the level of ACD depends on the concentration ratio of iron, chlorogenate and citrate (Hughes & Swain, 1962c). The ratio varies between tubers and even between areas within tubers. The stability of the complex declines with decreasing tissue pH. The relationship between lower pH in tissues and higher citrate levels was highly significant.

ACD and tissue pH declined when the N:K ratio declined (Vertregt, 1968). There was evidence that the citrate content of tissues declined with increasing chloride, thus increasing levels of potash or decreasing chloride ions resulted in a lower pH and less ACD. However, a pot trial carried out by McCain UK in 1994 (Blades, R; personal communication) found least ACD with a high N:K ratio. Several authors have confirmed that high rates of potash had a marked effect in reducing ACD. Dickens *et al*. (1962) found this effect in 7 out of 19 experiments, with both potassium chloride and potassium sulphate having similar effects. Similarly, Wijmark (2005) in Sweden showed that site-specific potash fertiliser led to improved potato quality including ACD. More recently, Wang-Pruski *et al*. (2007) demonstrated a small benefit to potash fertilisation in one field experiment but not in a second, although the potassium levels in the soil were considered high.

From pot and field experiments, Vertregt (1968) considered that ACD could be predicted from the chlorogenic acid content in fresh, peeled potatoes, with the maximum allowed content around 1.5 mmol per kilogram dry matter. To keep the tissue pH low, the citrate content should be high, and this was achievable by applying ‘much’ potash and no chloride.

The degree of ACD is known to be cultivar-dependent and to vary with climatic conditions (Hughes & Mapson, 1967; Wang-Pruski *et al*., 2007). In general, the degree of darkening was reduced when climatic conditions and management practices resulted in conditions favourable for crop growth (Wang-Pruski *et al*., 2007). The degree of ACD generally increased under drier climatic conditions, in soil that was more susceptible to drought, and with delayed planting.

5.6. Acrylamide

There is limited research linking potash use and development of acrylamide. Studies in Germany showed that high levels of potash (and moderate levels of nitrogen fertiliser) in potato crops had a positive effect on numerous quality parameters in chips and crisps, including acrylamide content (Heuser, 2005).

In a pot experiment, Gerendás *et al.* (2007) showed that as nitrogen levels increased, asparagine and reducing sugars were substantially greater at low rates of potash application than at intermediate or high potash rates. It is claimed that this trial demonstrates the role of potash in reducing acrylamide precursor concentrations (Magen & Nosov, 2008).

Overall, to minimise acrylamide, it can be concluded that the potash level should be such that reducing sugars are at their lowest at harvest that is optimal for processing.

6. KEY CONCLUSIONS AND RECOMMENDATIONS

(Recommendations for new research are shown in bold)

Potassium (K) is an important nutrient for all agricultural crops. Adequate applications of potash (K_2O) fertiliser as manufactured fertiliser and/or organic manure are needed to maintain soil K fertility and in some cases to increase crop yield or quality. Potash use decisions need to take account of the potential for potash to increase tuber yields, any potential effects on tuber quality for storage and the fresh or processing markets, and to maintain a satisfactory level of soil K fertility for future crops in the rotation. Standard recommendations were revised in 2010 taking account of available and relevant research evidence, and informed experience. There were no significant changes to the potash recommendations in the Fertiliser Manual (RB209) compared to the previous edition published 10 years before.

The potato crop has the highest requirement for potash of all major arable crops – the average rate of manufactured potash fertiliser to maincrop potatoes between 2005-2010 was 221 kg K_2O/ha. Based on the typical cost of muriate of potash (KCl) in July 2011 (£330/t, 55 pence/kg K_2O), this application would cost around £122/ha, equivalent to the typical price of about 1 t/ha of ware potatoes. Thus, although potash fertiliser is expensive and any unnecessary application should be avoided, only a small increase in potato yield or quality is needed to cover the cost of this typical application.

Organic manures are commonly applied before potatoes are planted, to provide a soil conditioning effect and a supply of NPK nutrients. A typical application of c.40 t/ha of FYM will supply c.300 kg K_2O/ha potentially worth c.£160, but the British Survey of Fertiliser Practice indicates that only c.10% of this potash is allowed for when decisions are taken on the use of manufactured potash fertiliser. This clearly indicates scope for growers to make a larger allowance for the supply of potash from organic manures.

The evidence base for the current potash removal standard of 5.8 kg K_2O/t of tubers (used in England and Wales, and Scotland) is limited, and commonly makes use of old data on low yielding and outdated varieties. Based on a yield of 50 t/ha, use of this potash removal standard results in a potash replacement requirement of 50 x 5.8 = 290 kg K_2O/ha. Although it is recognised that there is significant variability around the current average removal standard of 5.8 kg K_2O/t tubers, and that some of the data are quite old, it is considered that the available scientific evidence supports use of this existing standard as a good working average for potash nutrient management decisions on farms growing potatoes. **However, since potash is increasingly expensive, new research is needed to confirm if the current standard is appropriate on modern varieties, and to try and better understand the factors that influence variability in the standard between different crops and environmental conditions (e.g. soil type, soil analysis). The work could address the same questions for phosphorus (P) where the current standard is 1.0 kg P_2O_5/t tubers.**

Experimental data on the yield response of maincrop potatoes to potash application, show that there can be small yield responses to potash especially at low soil K Indices, but there is no evidence to support higher K rates than are needed for replacing the removal of potash in tubers, based on a potash offtake of 5.8 kg K_2O/ha.

However, these data are mostly old, with the experiments carried out on outdated varieties and growing systems. In other words, a 50 t/ha crop requires 290 kg K2O/ha to replace potash offtake, which (from the experimental evidence) will be higher than the amount of potash needed for maximum yield. Land owners and tenants should apply potash that will maintain the target level of soil K for the rotation (soil K Index 2- in England and Wales, soil M status in Scotland) which is recommended for sustainable agricultural production from most arable crops and grassland. Where land is rented out for short-term contract growing of potatoes, the same principle of potash use should apply, and should be achieved through agreement between the land owner/tenant and the potato grower.

Research suggests that application of potash at rates for maximum yield is sufficient to minimise the risk of bruising (blackspot). The use of higher rates to achieve further reduction gives benefits that are too small and inconsistent to be of practical value. Most reports suggest a reduction in specific gravity or percentage dry matter with increasing rates of potash fertiliser. Potassium chloride has been shown to result in a larger reduction in tuber dry matter concentration compared to use of potassium sulphate or nitrate, but the effect is inconsistent. It is unclear if applying potassium chloride well in advance of planting would have any additional effect on dry matter content.

Research evidence indicates that the effect of potassium on Enzymic Browning was not large, and was mainly observed on soils that were low or deficient in potassium. It is concluded that extra potash above that needed to replace potash removal is not required to reduce Enzymic Browning. The effect of potash on fry colour has been variable. In response experiments, the largest improvement in fry colour, usually statistically significant, came from the first increment of potash. Further Improvements in fry colour diminished with higher potash rates, and these improvements were rarely significant. Once again, it can be concluded that potash should be applied to replace offtake even where fry colour is the major concern. The effect of potash on After-Cooking Darkening is variable and other climatic and management factors may be more important. To minimise acrylamide, it can be concluded that the potash rate should be such that reducing sugars are at their lowest at harvest, that is optimal for processing. Overall, the research suggests that levels of potash that give optimum yield, and are sufficient to replace potash offtake, are also sufficient to reduce quality defects. There is no evidence to indicate that higher rates provide any consistent or significant improvement.

There is a need for new research relevant to modern day potato crops and growing systems to underpin future recommendations that can be used by growers with confidence, and to confirm if the high potash rates recommended by some processors can be justified. The research should be designed to understand the yield and quality effects of different rates, forms (potassium chloride, potassium sulphate) and timing of potash application to modern varieties of different determinancy groups (i.e. rooting pattern, possibly Cabaret and Markies for processing, Hermes for crisps and/or modern table varieties). If possible, the impact of different growing systems should be assessed, comparing potentially 'high nutrient efficiency' systems (e.g. irrigated, bed system, de-stoned, placed fertiliser) with expected 'low nutrient efficiency' systems (e.g. un-irrigated, ridge and furrow, not destoned, broadcast fertiliser).

In some areas (notably Cleveland, Yorkshire, Nottinghamshire and surrounding counties), where magnesian lime has been used in the rotation for decades as the usual and local source of agricultural lime, soil Mg Indices can be very high (Index 5 and over) with the ratio of soil K:Mg (mg/l) less than 0.5:1. There are strong anecdotal suspicions that potassium shortages in potatoes can be induced where soil magnesium levels are unnecessarily high. From first principles, higher rates of potash would be expected to be needed where there is an imbalance of soil K:Mg. It has been estimated that around 13% of the potato area might be grown on soils with a high soil Mg Index. **New research is needed to confirm if different potash recommendations should apply on high Mg soils, and to provide a basis for potash recommendations according to the ratio of soil K and Mg levels.**

7. Acknowledgements

The authors would like to thank the following organisations and individuals for the provision of information and/or their helpful advice and comments during the preparation of this report.

- McCain Foods Ltd for technical comments and supplying unpublished field trial data.
- The Potash Development Association for supplying source data on the potash content of potato tubers.

8. REFERENCES

Allison (2000). The magnesium, potassium and nitrogen nutrition of Estima. Report of project 807/182, British Potato Council.

Allison, M.F., Fowler, J.H. and Allen, E.J. (2001). Responses of potato (*Solanum tuberosum*) to potassium fertilisers. Journal of Agricultural Science, 136, 407-426.

Archer, F.C., Victor, A. and Boyd, D.A. (1976). Fertiliser requirements of potatoes in the Vale of Eden. Experimental Husbandry, 31, 72-79.

Baerug, R. and Enge, R (1974). Influence of potassium supply and storage conditions on the discoloration of raw and cooked potato tubers of cv. Pimpernel. Potato Research, 17, 271-282

Birch, J.A., Devine, J.R., Holmes, M.R.J. and Whitear, J.D. (1967). Field experiments on the fertiliser requirements of potatoes. Journal of Agricultural Science, 69, 13-24.

Boyd, D.A. and Dermott, W. (1964). Fertiliser experiments on maincrop potatoes 1955-61. Journal of Agricultural Science, 63, 249-263.

BSFP, (2010). British Survey of Fertiliser Practice, BSFP Authority. Defra Statistics, York. ISBN 978-0-95525-696-7

Burton, W.G. (1996). The Potato (2nd edition). Veenman & Zonen NV, The Netherlands.

Chamberland, E, and Scott, A (1968). N-P-K experiments in the lower St Lawrence region of Quebec. American Potato Journal, 45, 93-102.

Chapman, K.S.R., Sparrow, L.A., Hardman, P.R., Weight, D.N. and Thorp, J.R.A. (1992). Potassium nutrition of Kennebec and Russet Burbank potatoes in Tasmania: Effect of soil and fertiliser potassium on yield, petiole and tuber potassium concentrations and tuber quality. Australian Journal of Experimental Agriculture, 32, 521-527.

Craighead, M.D. and Martin, R.J. (2002/3). Fertiliser responses in potatoes - an overview of past Ravensdown research. Agronomy New Zealand, 32/33, 15-25.

Dampney (1994). Soil magnesium and potassium levels in England and Wales. Report to the Potash Development Association.

Davenport, J.R. and Bentley, E.M. (2001). Does potassium fertiliser form, source and time of application influence potato yield and quality in the Columbia Basin? American Journal of Potato Research, 78, 311-318.

Defra (2010). The Fertiliser Manual (RB209), 8th edition. TSO, Norwich or www.defra.gov.uk/RB209.

DGER/SCPA, (1992). French Ministère de l'Agriculture et de la Pêche DGER and SCPA, Centre de Recherches, 68700 Aspach le Bas, France. Experiments on the uptake and offtake of nutrients by different arable crops.

Dickins, J.C., Harrap, F.E.G. and Holmes, M.R.J. (1962). Field experiments comparing the effects of muriate and sulphate of potash on potato yield and quality. Journal of Agricultural Science, 59, 319-326.

Dubetz, S. and Bole, J.B. (1975). Effect of nitrogen, phosphorus and potassium fertilisers on yield components and specific gravity of potatoes. American Potato Journal, 52, 390-405.

Duengeverordnung (1996). German Ordinance on Fertilisation. Pers. Comm., Potash Development Association.

Dwelle, R.B., Stallknecht, G.F., McDole, R.E. and Pavek, J.J. (1975). Effects of soil potash treatment and storage temperature on blackspot bruise susceptibility of four *Solanum tuberosum* cultivars. American Potato Journal, 52, 277-278.

Dwelle, R.B., Stallnecht, G.F., McDole, R.E. and Pavek, J.J. (1977). Effect of soil potash treatment and storage temperature on blackspot bruise development in tubers of four *Solanum tuberosum* cultivars. American Potato Journal 54, 137-146.

Eagle (1967). Release of non-exchangeable potassium from certain soils. In *Soil Potassium and Magnesium*, MAFF Technical Bulletin 14, 49-54, London.

Eastwood, T and Watts, J. (1956). the effect of potash fertilisation on chipping quality III – chip color. American Potato Journal 33, 255-257.

Farrar, K. and Boyd, D.A. (1976). Experiments on manuring of maincrop potatoes on soils of Ross series. Experimental Husbandry, 31, 64-71.

Furunes, J (1990). Nitrogen and potassium for potatoes. Norsk Landbruksforsking, 4, 179-188.

Gerendás, J., Heuser, F. and Sattelmacher, B. (2007). Influence of nitrogen and potassium supply on contents of acrylamide precursors in potato tubers and on acrylamide accumulation in french fries. Journal of Plant Nutrition, 30, 1499–1516.

Gunasema, H.P.M. (1969). Studies on the growth of potato with specific reference to the efficient use of nitrogen and potassium. pH.D. Thesis, Reading University.

H Magen, H. and Nosov, V. (2008). Putting potassium in the picture: achieving improved nitrogen use efficiency. Bangladesh Journal of Agriculture and Environment, 4: 115-127, Special Issue.

Haberland, R. (2006). Balance between yield and quality. Neue Landwirtschaft, 2006, 47-49.

Harrap, F.E.G. (1960). Some aspects of the potash nutrition of the potato. Journal of the Science of Food and Agriculture, 11, 295-298.

Harrison, H.C., Bergman, E.L. and Cole, R.H. (1982). Growth responses, cooking quality determinations and leaf nutrient concentrations of potatoes as related to exchangeable calcium, magnesium and potassium in the soil. American Potato Journal, 59, 113-124.

Herlihy, M., and Carroll, P.J. (1969). Effects of N, P and K and their interactions in yield, tuber blight and quality of potatoes. Journal of the Science of Food and Agriculture, 20, 513-517.

Heuser, F., Gerendás, J., Sattelmacher, B. and Verlag Th. Mann. (2005). The effect of N- and K-fertilisation on the contents of reducing sugars and free amino acids: Importance for the acrylamide content of potato chips. Kartoffelbau, 7, 308-313.

Hewitt E.J. (1983). The essential and functional mineral elements. In: Diagnosis of mineral disorders in plants – Principles. 7-53, HMSO, London.

Hojmark, J.V. (1977). Effects of increasing rates of KCl and K_2SO4 on potato yield, cooking quality and colour of chips. Tiddskrift for Planteavl, 81, 68-80.

Horneburg, B., and Wirsing, F. (1995). The tendency of potato tubers to black spot. 2. Influence of fertiliser application and irrigation on the expression of black spot. Kartoffelbau, 46, 318-320.

Hughes, J.C., and Evans, J.L. (1967). Studies on after-cooking blackening IV. After-cooking blackening in potatoes IV. European Potato Journal, 10, 16-36.

Hughes, J.C., Ayers, J.E. and Swain, T. (1962a). After-cooking blackening in potatoes I. Journal of the Science of Food and Agriculture, 13, 224-229.

Hughes, J.C. and Mapson, L.W. (1967). Proceedings 2nd International Congress of Food Science Technology (Warsaw 1966), 119-135.

Hughes, J.C., and Swain, T. (1962b). After-cooking blackening in potatoes II. Journal of the Science of Food and Agriculture, 13,229-236.

Hughes, J.C., Swain, T. (1962c). After-cooking blackening in potatoes III. Journal of the Science of Food and Agriculture, 13,358-363.

Jacob, W.C. (1959). Studies on internal black spot in potatoes. Mem. Cornell Univ. agric. Exp. Stn. 368.

Johnson, E.W. and Zemroch, P.J. (1980). The manuring of potatoes on warp soils. Experimental Husbandry, 37, 94-109.

Juul, F. (1949). Studier over kartoflens morkfarvning efter kogning. Kobenhavn, Jul. Gjellerups Forlag.

Kiermeier, F. and Rickerl, E. (1955). Uber die Ursachen der Verfarbung gedampfter Kartoffeln. Z. Lebensm.-Untersuch. U. –Forsch, 102, 441-449.

Kunkel, R., Holstad, N. and Russell T.S. (1973). Mineral element content of potato plants and tubers vs yields. American Journal of Potato Research, 50, No 8, 275-282.

Kunkel, R. and Gardner, W.H. (1965). Potato tuber hydration and its effect on blackspot of Russet Burbank potatoes in the Columbia Basin of Washington. American Potato Journal, 42, 109-124.

Kunkel, R., Gardner, W.H. and Holstad, N.M. (1986). Improvement of techniques for potato blackspot evaluation and some errors associated with measurements. American Potato Journal, 63, 13-23.

Kunkel, R. and Holstad, N. (1972). Potato chip color, specific gravity and fertilisation of potatoes with N-P-K. American Potato Journal, 49, 43-62.

Laboski, C.A.M. and Kelling, K.A. (2007). Influence of fertiliser management and soil fertility on tuber specific gravity: A review. American Journal of Potato Research, 84, 283-290.

Laughlin (1962a). Spray concentrations of potassium chloride and potassium sulphate affect potato growth, yield and chemical composition. American Potato Journal, 39, 100-106.

Laughlin, (1962b). Soil and foliar applications of nutrients affect dry matter and foliar necrosis. American Potato Journal, 39, 125-134.

Loué, A. (1977). Fertilisation et nutrition minérale de la pomme de terre. Expérimentation et études agronomiques. SCPA, Mulhouse, 147.

Maier, N.A., Dahlenberg, A.P. and Frensham, A.B. (1986). Potassium nutrition of irrigated potatoes in South Australia. 3. Effects on specific gravity and internal bruising. Australian Journal of Experimental Agriculture, 26, 737-744.

Maier, N.A., Dahlenberg, A.P. and Williams, C.M.J. (1984). Effects of nitrogen, phosphorus and potassium on yield, specific gravity, crisp colour and tuber chemical composition of potato (*Solanum tuberosum* L) cv. Kennebec. Australian Journal of Experimental Agriculture, 24, 813-824.

McDole, R.E. (1978). Potassium fertiliser trials with potatoes on course tectured soils in southeastern Idaho. American Potato Journal 55, 161-170.

McDole, R.E., Halkneckt, G.F., Dwelle, R.B. and Pavek, J.J. (1978). Response of four potato varieties to potassium fertilisation in a seed growing area of eastern Idaho. American Potato Journal, 55, 495-504.

McGarry, A, Hole, C.C., Drew, R.L.K. and Parsons, N. (1996). Internal damage in potato tubers: a critical review. Postharvest Biology and Technology, 8, 239-258.

McNabnay, M., Dean, B.B., Bajema, R.W. and Hyde, G.M. (1999). The effect of potassium deficiency on chemical, biochemical and physical factors commonly associated with blackspot development in potato tubers. American Journal of Potato Research, 75, 53-60.

Milford, G.F.J. and Johnston, A.E. (2007). Potassium and nitrogen interactions in crop production. *Proceedings International Fertiliser Society* **615**, 23pp.

Mulder, E.G.(1949). Mineral nutrition in relation to the biochemistry and physiology of potatoes. Plant Soil, 2, 59-121.

Mundy, N.I. and Munsh, C.B. (1993). Effect of type of potassium fertiliser on enzymatic discoloration and phenolic, ascorbic acid, and lipid contents of potatoes. Journal of Agricultural and Food Chemistry, 41, 849-852.

Murphy, H.J. and Goven, M.J. (1959). Potash and processing potatoes. Maine Farm Research, 7, 3-8.

Murphy, H.J. and Goven, M.J. (1966). The last decade in 38 years of potash studies for potato fertilisers in Maine. American Potato journal, 43, 122-128.

Oortwijn Botjes, J; Verhoeven, W.L. (1927). Het blauw worden van aardappelen. Tijdschr. PlZiekt., 33, 57-96.

PAAG (2010). Collation of data from routine soil analysis. Report of the Professional Agricultural Analysis Group for 2009/2010, www.nutrientmanagement.org.

Panique, E., Kelling, K.A., Schulte, E.E., Hero, D.E., Stevenson, W.R. and James, R.V. (1997). Potassium rate and source effects on potato yield, quality and disease interaction. American Potato Journal, 74, 379-398.

Perrenoud (1993). Fertilising for high yield potato. IPI Bulletin 8, International Potash Institute, Basel.

Perrenoud, S (1993) Potato fertilisers for yield and quality. 2nd edition. International Potash Institute Bulletin No. 8. Basel, Switzerland.

Peterson, L.A., Weis, G.G. and Walsh, L.M. (1971). Potato response to varying levels of soil test P and K. Communications in Soil Science and Plant Analysis, 2, 267-274.

Potato Council (2010a). Production and price trends 1960-2009. www.potato.org.uk.

Potato Council (2010b). Consumption and processing in GB. www.potato.org.uk.

Prummel (1973). Kalibemesting en blauwgevoeligheid van aardappelen. Bedrijfsontwikkeling, 4, 595-599.

Prummel, J. (1981). Potassium fertilisation and potato quality. Kartoffelbau, 32, 73-76.

Prummel, J. (1986). Effect of potassium on susceptibility of potato tubers to blackening. Rapport, Instituut voor Bodemvruchtbaarheid, Netherlands, 1986, 12, 29pp.

Redulla, C.A., Davenport, J.R., Evans, R.G., Hattendorf, M.J., Alva, A.K. and Boydston, R.A. (2002). Relating potato yield and quality to field scale variability in soil characteristics. American Journal of Potato Research, 79, 317-323.

Roberts, S. and Beaton, J.D. (1988). Potato use of phosphorus and potassium in sandy soils. Washington State University Research Bulletin XB1004, Pullman, Washington, USA.

Russell, E.W. (1973). Soil conditions and plant growth (10th edition). Longmans Press.

Sandstra, H.G., Anderson, R.H. and Dawley, W.K. (1968). Effects of fertiliser on yield and quality on Norland potatoes in northeastern Saskatchewan. American Potato Journal, 46, 69-74.

Schippers, P.A. (1968). The influence of nitrogen and potassium application on the yield and specific gravity of four potato varieties. European Potato Journal, 11, 23-33.

Scudder, W.T., Jacob, W.C. and Thompson, H.C. (1950). Varietal susceptibility and the effect of potash on the incidence of blackspot in potatoes. Proceedings American Society of Horticultural Science, 56, 343-348.

Sharma, U.C. and Aurora, B.R. (1988). Effect of applied nutrients on the starch, proteins and sugars in potatoes. Food Chemistry, 30, 313-317.

Silva, G., Chase, R.W. and Kitchen, R.B. (1989). Effects of potassium source and rate on potato quality. American Potato Journal, 66, 543-544.

Sinclair, A.H., Shipway, P. and Wale, S.J. (2010). Phosphorus, potassium, sulphur and magnesium recommendations for cereals, oilseed rape and potatoes. Technical note 633, SAC Consulting, Edinburgh.

Skinner, R.J. and Todd, A.D. (1998). Twenty-five years of monitoring pH and nutrient status of soils in England and Wales. Soil Use and Management, 14, 162-169.

Stanley, R. and Jewel, S. (1989). The influence of source and rate of potassium fertiliser on quality of potatoes for French fry production. Potato Research, 32, 439-446.

Stark, J.C. and Love, S.L (2003). Tuber quality. In JC Stark, SL Love (Editors) Potato Production Systems. University of Idaho Extension, Moscow, Idaho, USA. Pp329-343.

Terman, G.L., Carpenter, P.N. and Cunningham, C.E. (1953). Relation of soil and fertiliser potassium to dry matter content and yield of potatoes. Soil Science, 75, 449-458.

Timm, H. and Merkle, F.G. (1963). The influence of chlorides on yield and specific gravity of potatoes. American Potato Journal, 40, 1-8.

Van Loon, C.D. and Van den Berg, W. (2003/4). The effect of chloride fertilisation on blackspot susceptibility and other quality characteristics and on yield of potato. Potato Research, 46, 147-154.

Veerman, A. (2001). Variation of tuber quality between and within lots of ware potato cultivars. PhD thesis (Dutch with English summary), Wageningen University, The Netherlands, 253pp.

Vertegt, N. (1968). After-cooking discolouration of potatoes. European Potato journal, 11, 226-234.

Vertregt, N. (1968). Relation between black spot and composition of the potato tuber. European Potato Journal, 11, 34-44.

Wang-Pruski, G., Zebath, B.J., Leclerc, Y., Arsenault, W.J., Botha, E.J., Moorehead, S. and Ronis, D. (2007). Effect of soil type and nutrient management on potato after-cooking darkening. American Journal of Potato Research, 84, 291-299.

Webber, J., Boyd, D.A. and Victor, A. (1976). Fertilisers for manincrop potatoes on magnesian limestone soils: experiments in Yorkshire 1966-71. Experimental Husbandry, 31, 80-90.

Welte, E. and Mulder, K. (1966). European Potato Journal, 9, 36-45.

Westermann, DT; James, DW; Tindall, TA; Hurst, RL (1994) Nitrogen and potassium fertilisation of potatoes: sugars and starch. American Potato Journal, 71, 433-453.

White, R.P., Munro, D.C. and Sanderson, J.B. (1974). Nitrogen, potassium and plant spacing effects on yield, tuber size specific gravity and tissue N, P and K of Netted Gem potatoes: Yield and specific gravity. Canadian Journal of Plant Science, 54, 535-539.

Widdowson, F.V. and Penny, A. (1975). Results from experiments measuring the effects of large amounts of an NPK fertiliser on yield, tuber size and N, P and K contents of there potato varieties. Journal of Agricultural Science,, 85, 515-525.

Wijkmark, L., Lindholm, R., Nissen, K. and Stafford, J.V. (2005). Uniform potato quality with site-specific potassium application. Precision agriculture '05. Papers presented at the 5th European Conference on Precision Agriculture, Uppsala, Sweden. Wageningen Academic Publishers, Wageningen, Netherlands. pp 393-400.

Wilcox, G.E. (1961). Effect of sulphate and chloride sources and rates of potassium on potato growth and tuber quality. American Potato Journal, 38, 215-220.

Winkelmann, H.H. (1992). Potassium fertiliser application to potatoes. Kartoffelbau, 43, 412-418.

Withers, P.J.A. (1991). Removal of phosphorus and potassium from the soil in wheat and barley straw. Journal of Agricultural Science, 117, 221-224.

Zehler, E., Kreipe, H. and Gething, P.A. (1981). Potassium sulphate and potassium chloride – their influence on the yield and quality of cultivated plants. International Potash Institute Bulletin No. 9. Basel, Switzerland.