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The effects of fertilizers and drought on the concentrations of potassium in the dry matter and tissue water of field-grown spring barley

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SUMMARY

The effects of N, P, K and Na silicate fertilizers, and drought on the concentrations of K in the dry matter and tissue water of field-grown spring barley crops have been investigated. Percentage K in dry matter depended on the amounts of N, P, K or water received by the crops and was linearly related to fresh weight to dry weight ratio, but the slope of this relationship depended on whether or not the crops received K. Expressing K concentrations on the basis of tissue water eliminated differences between crops, except for those given insufficient K. Barley crops given fertilizer K maintained K concentrations in their tissue water of about 200 mmol/kg tissue water for most of the growth period but crops grown without K had only 50–70 mmol/kg tissue water. The results indicate that K concentrations in the tissue water are a more reliable indicator of tissue K status than % K in dry matter.

Decreases in crop K content resulting from poor K supply were balanced by increases in Na and Ca (but not Mg) contents so that total cation concentrations in the tissue water were similar in low and high K crops. The extra Na and Ca are probably primarily involved in maintaining charge balance for anion absorption but once in the plant they may also substitute for K in its osmotic role.

INTRODUCTION

The measurement of concentrations of nutrients in crops is important for determining the relationships between nutritional status and growth (Bates, 1971), for predicting fertilizer requirements (Cooke, 1982) and for assessing crop quality (Cummings & Wilcox, 1968). If the measurements are to provide information about crop nutrient status it must be shown that decreases in concentrations are the result only of inadequate rates of supply of the nutrient of interest. When adequate levels of the nutrient are supplied other factors should be without effect. In most agronomic studies, tissue nutrient concentrations are expressed as a percentage in the dry matter (e.g. Chapman, 1966; Bates, 1971; Jarrell & Beverly, 1981; Jones, 1982). In another paper, we questioned the usefulness of this convention (Leigh & Johnston, 1983) and suggested that tissue water may provide a better basis for calculating nutrient concentrations. In this paper we further test this suggestion by examining the effect of various treatments on concentrations of K in the dry matter and tissue water of field-grown spring barley. Potassium was chosen because it is not metabolized and thus results are not complicated by having to consider different forms of the nutrient. Also, it has an important osmotic role so concentrations in the tissue water are likely to have physiological relevance (Wyn Jones, Brady & Spiers, 1979). The extent to which K-deficient barley is able to replace K by compensatory increases in other cations has also been reassessed, by examining the effects of these changes on total cation concentrations in the tissue water.

MATERIALS AND METHODS

Spring barley (*Hordeum vulgare* cv. Georgie or Julia) was sampled from two field experiments at Rothamsted. The first was the Hoosfield Continuous Barley Experiment. The design, described by Warren & Johnston (1967), was modified in 1968 when each plot was divided into four subplots which are given four rates of N (0, 48, 96, 144 kg/ha). The annual amounts of P, K and farmyard manure (FYM) applied to the sampled plots, and the levels

Table 1. *Manurial treatments given, and exchangeable cations and $NaHCO_3$-soluble P in soils from either the Hoosfield Continuous Barley or the Drought experiment*

Experiment	Manurial treatment P (kg/ha)	K (kg/ha)	Na (kg/ha)	FYM (t/ha)	Exchangeable cations in soil (mg/kg dry soil) K	Ca	Mg	Na	$NaHCO_3$ soluble P (mg/kg dry soil)
Hoosfield	—	—	—	35	827	4204	140	15	137
Continuous Barley*	—	90	—	—	382	2347	67	9	4
	35	—	—	—	55	4481	31	16	100
	35	90	—	—	329	2950	57	9	137
	35	—	63	—	57	5104	27	33	72
Drought†	23	44	—	—	165	3810	42	16	25

* Treatments applied since 1852. Na supplied as Na silicate (14% Na); FYM = farmyard manure which supplied in total 235, 45 and 340 kg/ha of N, P and K, respectively.

† Data of Legg *et al.* (1978).

of exchangeable cations and $NaHCO_3$-soluble P in the surface soils (0–23 cm) are given in Table 1. Results are presented for the 1981 experiment which was sown with cv. Georgie on 17 February. Sampling of the experimental plots began 66 days later (when the plants had three leaves) and continued every 3–5 days until the crop was harvested on 10 August.

The second experiment measured the effect of drought on barley, using mobile shelters to protect the crop from rainfall (Legg *et al.* 1978; Day *et al.* 1978). The results presented here are from the 1976 experiment described in detail by Day *et al.* (1978). Two crops were selected, one subjected to drought from emergence, the other trickle irrigated to maintain the soil water content near to field capacity (treatments 3 and 12 of Day *et al.* 1978). Both crops received 75, 23 and 44 kg/ha of N, P and K, respectively. The exchangeable cations and $NaHCO_3$-soluble P in the surface soils (0–23 cm) are given in Table 1. Barley, cv. Julia, was sown on 31 March 1976. It was first sampled 40 days later and on five subsequent occasions.

In both experiments, all above-ground parts of the crop were taken from a 1 m length of row on each sampling occasion. The samples, sealed in moisture-proof bags, were brought to the laboratory where fresh and dry weights were determined. Tissue was dried at 80 °C overnight. Tissue water was assumed to be the difference between fresh and dry weights. Cations were extracted from ashed tissue (450 °C, 3 h) with HCl and were measured by atomic absorption spectroscopy. Bicarbonate-soluble P was extracted from air-dried soils with 0·5 M-$NaHCO_3$ at pH 8·5 (Olsen *et al.* 1954) and was measured using a Technicon AutoAnalyzer (Salt, 1968). Exchangeable cations were leached from the soil with 1 M ammonium acetate (Metson, 1956) and were determined by atomic absorption spectroscopy.

RESULTS

Cation and P contents of soils

The various manurial treatments affected the exchangeable cations and $NaHCO_3$-soluble P in the surface soils (Table 1). On Hoosfield exchangeable K was between 330 and 380 mg/kg on plots given K fertilizer but decreased to about 55 mg/kg in soils which had not received K since 1852. At Rothamsted growth of barley responds to K fertilizer when exchangeable K is below 120 mg/kg (Johnston, Warren & Penny, 1970); thus on the low K plots growth is limited by K supply. The exchangeable K in plots receiving K as FYM was over twice that of plots given K fertilizer (Table 1). FYM also increased soil Mg. Calcium was high in all soils but Na was generally low and was increased only slightly by the addition of Na silicate. In soils receiving P as fertilizer or FYM, $NaHCO_3$-soluble P was above the level (15 mg/kg) at which barley responds to P at Rothamsted (A. E. Johnston, unpublished results) but was below this level in soil not given P since 1852. Soils from the drought experiment had adequate amounts of all nutrients (Table 1). Barley crops grown without N, P or K showed deficiency symptoms of the nutrient which was lacking and their growth was restricted throughout the growing season. The fully irrigated crop grew faster than the crop subjected to drought, particularly during the latter part of the season.

% K in the dry matter

Percentage K in the dry matter initially increased and then declined steadily until harvest (Fig. 1; see

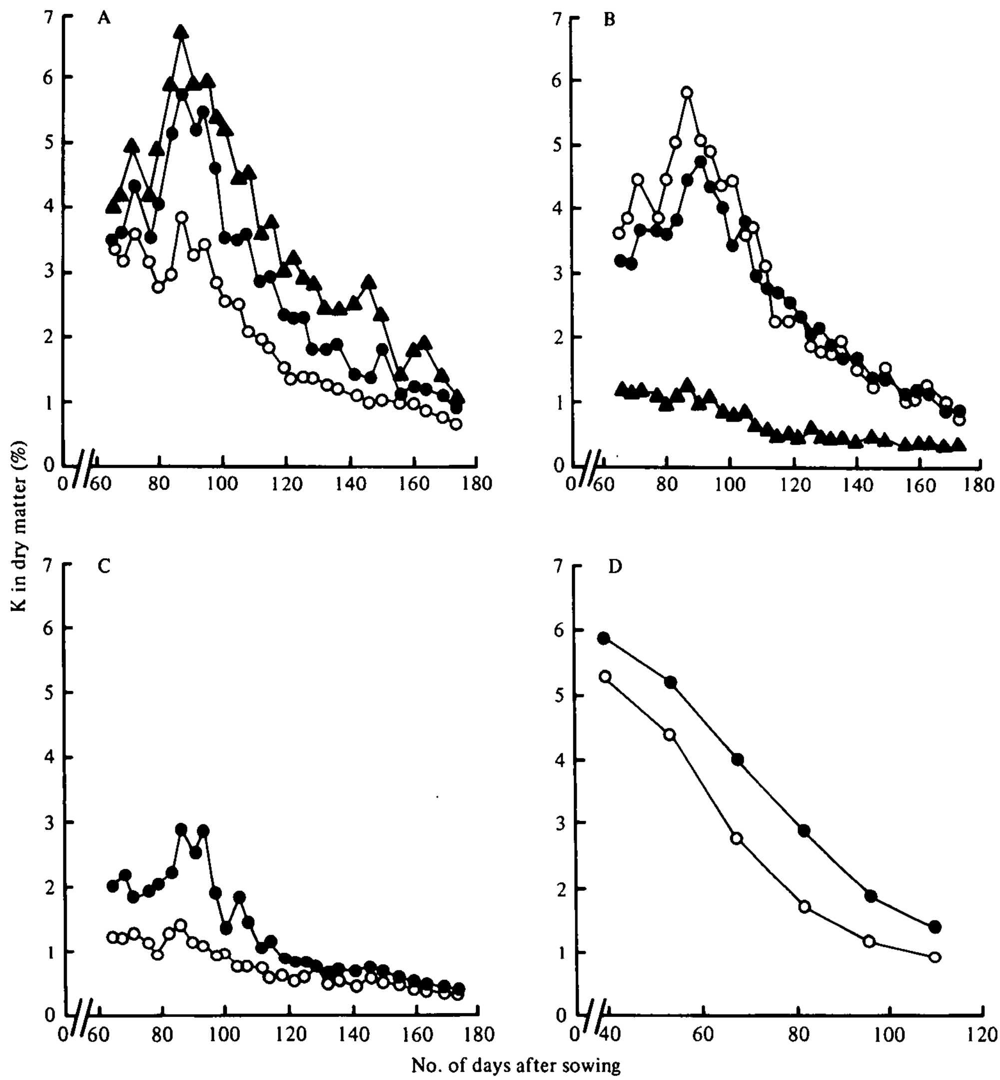

Fig. 1. Percentage K in dry matter in field-grown spring barley crops from the 1981 Hoosfield Continuous Barley (A–C) or 1976 Drought (D) experiments. Crops grown with A: ▲, FYM plus 144 kg N/ha; ○, P and K but no N; ●, P and K plus 144 kg N/ha; B: 96 kg N/ha plus ○, P and K; ●, K only; ▲, P only; C: 48 kg N/ha plus ○, P only; ●, P and Na silicate; D: fully irrigated (●), fully droughted (○). P, K, FYM and Na silicate were supplied at the rates given in Table 1.

also Leigh & Johnston, 1983). The increase was not seen in crops from the drought experiment (Fig. 1D) because samples were taken less frequently. At all times during growth, the K concentration in the dry matter was affected by treatment. The lowest values were in crops receiving no K (Figs 1B and C) and highest values were in crops given FYM (Fig. 1A). These differences appear to reflect differences in soil K (Table 1). In crops given fertilizer K, values of percentage K in dry matter were intermediate between the two extremes and depended on the rate at which N or P or water was supplied (Figs 1A, B and D). Low rates of supply of these resulted in lower K concentrations in the dry matter. Sodium silicate, which was without effect on exchangeable soil K (Table 1), increased % K in dry matter in crops which did not receive K (Fig. 1C). Lack of P decreased % K in dry matter only during early growth (Fig. 1B) but for all other factors the effects were apparent throughout growth.

For all crops, % K in dry matter was linearly

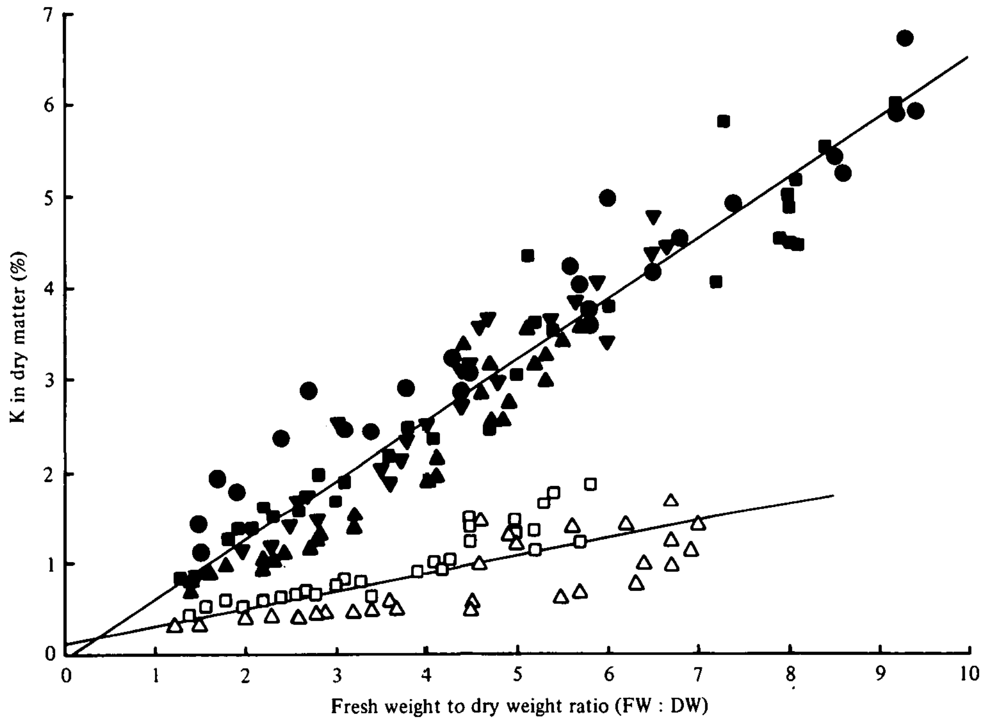

Fig. 2. Relationship between fresh weight to dry weight ratio (FW:DW) and %K in dry matter for spring barley crops from the 1981 Hoosfield Continuous Barley experiment. Each point represents a single sample taken during the growth of the crops. Crops received: ●, FYM plus 144 kg N/ha; ▲, P and K plus 0 kg N/ha; ■, P and K plus 144 kg N/ha; ▼, K plus 96 kg N/ha; □, P plus 0 kg N/ha; △, P plus 144 kg N/ha. P, K and FYM were supplied at the rates given in Table 1. Lines were fitted by regression and have the equation $y = 0{\cdot}65x - 0{\cdot}06$ (solid symbols) and $y = 0{\cdot}19x + 0{\cdot}1$ (open symbols).

related to fresh weight to dry weight ratio (FW:DW) but the slope of the relationship depended on whether or not the crops were given K (Fig. 2). Crops given K as FYM showed the same relationship as those given K fertilizer even though FYM doubled exchangeable soil K (Table 1). The slope of the line for these crops was greater than that for crops grown without K. Effects due to different rates of supply of N or P were eliminated. These results suggest that calculating K concentrations on the basis of fresh weight or tissue water should reduce many of the differences in K concentrations in Fig. 1. Tissue water rather than fresh weight was chosen as the basis for expressing K concentrations because it has physiological relevance (Leigh & Johnston, 1983).

K concentrations in tissue water

All crops given K, either as fertilizer or FYM, maintained K concentrations of about 200 mmol/kg tissue water throughout most of growth, irrespective of the amount of N or P or water they received (Fig. 3). The concentrations increased rapidly at the end of the growing season as the crop senesced and water loss increased. This increase occurred earlier in crops given N or FYM or which were subjected to drought (Fig. 3A and D). Barley crops given neither K nor Na silicate showed a similar overall pattern of behaviour to K sufficient crops except that the concentrations maintained during the constant phase were only 50–70 mmol/kg tissue water (Fig. 3C). Sodium silicate increased this concentration to about 100 mmol/kg tissue water (Fig. 3C).

Concentrations of other cations in low and high K barley crops

In barley well supplied with K this nutrient accounted for 70–85% of the total cations (K + Ca + Mg + Na) calculated as mmol/kg tissue water (Fig. 4A). Calcium was the next most abundant (15–25%) whilst Mg and Na accounted for only about 3 and 1%, respectively. In crops deprived of K these proportions changed (Fig. 4B).

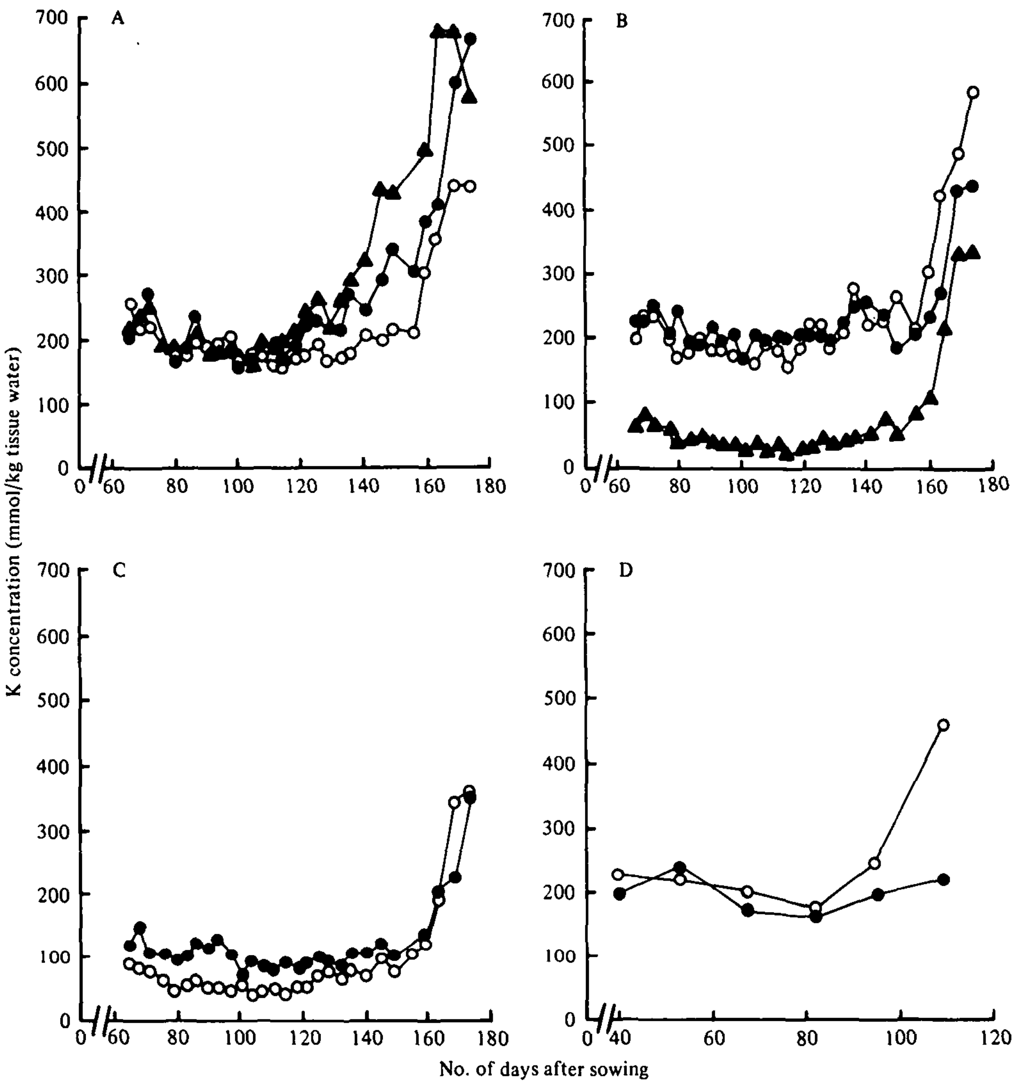

Fig. 3. Potassium concentrations in the tissue water of field-grown spring barley crops from the 1981 Hoosfield Continuous Barley (A–C) and 1976 Drought (D) experiments. Crops grown with A: ▲, FYM plus 144 kg N/ha; ○, P and K but no N; ●, P and K plus 144 kg N/ha; B: 96 kg N/ha plus ○, P and K; ●, K only; ▲, P only; C: 48 kg N/ha plus ○, P only; ●, P and Na silicate; D: crops fully irrigated (●), fully droughted (○). P, K, FYM and Na silicate were supplied at the rates given in Table 1.

Potassium accounted for 25–35 % of the total, Ca for 35–40 % and Na for 25–35 %. Magnesium, however, was still only about 5 % of the total. The net effect was that total cation concentrations, expressed on a tissue water basis, were only slightly reduced in K deficient plants (Fig. 5A). The changes in proportions of the various cations thus represent real changes in their concentrations. These changes in concentration depended only on K; N and P were without effect (not shown).

DISCUSSION

The measurement of crop K status

Percentage K in dry matter is not a reliable measure of the K status of cereals because it depends not only on the level of soil K but also on the rates of supply of N, P, Na silicate and water (Fig. 1). It is thus impossible to determine whether it is responding to K supply or to these other factors. Also, % K in dry matter varies with age

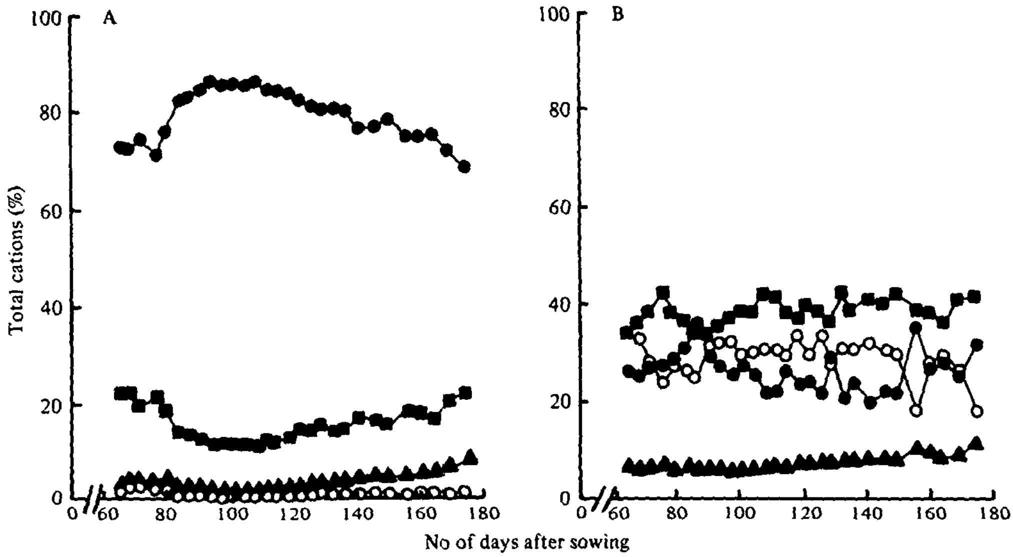

Fig. 4. The percentage of total cations (K + Ca + Mg + Na; calculated as mmol/kg tissue water) accounted for by K (●), Ca (■), Mg (▲) and Na (○) in spring barley from the 1981 Hoosfield Continuous Barley Experiment. Crops were grown with (A) or without (B) K fertilizer. The crops received P fertilizer and 144 kg N/ha. Rates of supply of P and K are given in Table 1.

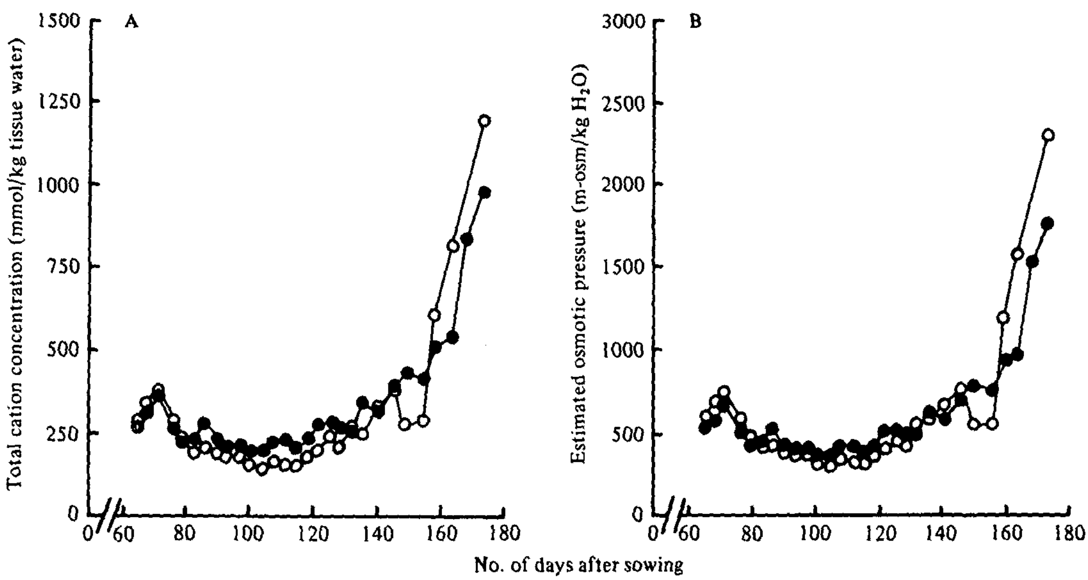

Fig. 5. Total cation concentrations in the tissue water (A) and calculated osmotic pressure generated by K + Na + Ca (B) for spring barley crops from the 1981 Hoosfield Continuous Barley Experiment. Crops were grown with (●) or without (○) K fertilizer. The crops received P fertilizer and 144 kg N/ha. Rates of supply of P and K are given in Table 1. The osmotic pressure was calculated on the assumption that the cations were present as their chloride salts.

(Fig. 1) so deficiencies can only be detected if crops are compared at the same age to minimize this time-dependent change. This means that the %K value expected in a K-sufficient crop must be known for each stage of crop development. In contrast, K concentrations in the tissue water remained relatively constant throughout most of growth, were not affected by the rate of supply of N, P or water and were decreased only in crops which received no K (Fig. 3). Where N was given, the increase in the K concentration at the end of the growing season occurred earlier (Fig. 3A). A similar, earlier increase also occurred in the crop subjected to drought (Fig. 3D), suggesting that the increase is related to more rapid depletion of soil water. The earlier increase seems to occur only in crops receiving more than 100 kg N/ha (compare crops in Figs 3A and B; R. A. Leigh and A. E. Johnston, unpublished results).

Barley crops well supplied with K maintained K concentrations of about 200 mmol/kg tissue water, irrespective of the exchangeable K in the soil (compare K-fertilizer and FYM treatments in Fig. 3A for soils with 329 and 827 mg exchangeable K/kg). Barley crops grown in nutrient solutions with adequate K also maintain K concentrations of about 200 mmol/kg tissue water (Asher & Ozanne, 1967; Pitman, 1972; Ahmad & Wyn Jones, 1982) and this seems to represent the level to which this nutrient is accumulated in K-sufficient barley. In contrast, barley grown without K, and which showed visible signs of K deficiency, maintained much lower K concentrations in tissue water (Figs 3B and C). Thus K deficiency in barley can be detected as a significant reduction in K concentration below 200 mmol/kg tissue water. Because K concentrations remain relatively constant throughout much of the growing season this comparison can be made between plants of different ages. A 'critical' K concentration expressed on the basis of tissue water should thus be age independent, unlike 'critical' nutrient concentrations in dry matter which decline with age (Bates, 1971). Using this method of assessment it can be seen that Na silicate increased the K concentration in the tissue water of barley grown without K (Fig. 3C). However, the K concentration was still less than that in a crop given sufficient K. The mechanism underlying this Na silicate-dependent effect is not understood. Similar observations have been reported by Johnston (1969) for winter wheat grown with Na_2SO_4 on an equally K-deficient soil.

If K concentrations in tissue water are to be measured in field-grown crops precautions must be taken to prevent water loss from samples. Even with precautions, however, we found some day-to-day variation in K concentration in the tissue water (Fig. 3). This was probably caused by changes in weather and because crops were sampled at different times of the day. The variation might be reduced by collecting samples early in the morning when tissue water potential is at a maximum (Fitter & Hay, 1981) or by relating K concentrations to maximum potential water content (Barrs & Weatherley, 1962). Daily fluctuations in water content do not prevent recognition of acute K deficiency (Fig. 3) so such procedures are likely to be of most value when small differences in K status are being investigated.

Replacement of K by other cations in low-K barley

It seems likely that the primary mechanism underlying the increased Na and Ca concentrations in barley grown without K is the need to maintain charge balance for anion uptake, but once absorbed the extra Ca and Na may also act as osmotica. Calculation of the osmotic pressure which would be generated by K+Ca+Na salts, if they were all osmotically active, shows that these could be similar in both low and high K barley crops (Fig. 5B). While it is unlikely that all Ca is osmotically active, this does indicate that in field-grown barley some osmotic balancing could be achieved by uptake of extra Ca and Na. Expressed sap from leaves of low K *Phaseolus* plants contained high concentrations of soluble Ca (Mengel & Arneke, 1982) confirming the possibility that it is an osmotically-important solute when K is absent. This contrasts with barley seedlings grown in dilute $CaSO_4$ which have low K contents but high levels of reducing sugars (Pitman, Mowat & Nair, 1971). This suggests that plants may have a number of strategies available to them to maintain sap osmotic pressure (or turgor) in the absence of K. The method employed may be governed by the need to maintain charge balance and the availability of inorganic salts. If the latter are available and anion uptake is rapid, high concentrations of substituting cations may be expected. If, however, cations are unavailable or anion uptake is low, reducing sugars may be accumulated.

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REFERENCES

Ahmad, N. & Wyn Jones, R. G. (1982). Tissue distribution of glycinebetaine, proline and inorganic ions in barley at different times during the plant growth cycle. *Journal of Plant Nutrition* **5**, 195–205.

Asher, C. J. & Ozanne, P. G. (1967). Growth and potassium content of plants in solution cultures maintained at constant potassium concentrations. *Soil Science* **103**, 155–161.

Barrs, H. D. & Weatherley, P. E. (1962). A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Australian Journal of Biological Sciences* **15**, 413–428.

Bates, T. E. (1971). Factors affecting critical nutrient concentrations in plants and their evaluation: a review. *Soil Science* **112**, 116–130.

Chapman, H. D. (1966). *Diagnostic Criteria for Plants and Soils.* University of California, Division of Agricultural Sciences.

Cooke, G. W. (1982). *Fertilizing for Maximum Yield.* London: Granada Publishing Ltd.

Cummings, G. A. & Wilcox, G. E. (1968). Effect of potassium on quality factors – fruits and vegetables. In *The Role of Potassium in Agriculture* (ed. V. J. Kilmer, S. E. Younts and N. C. Brady), pp. 243–267. Wisconsin: American Society of Agronomy.

Day, W., Legg, B. J., French, B. K., Johnston, A. E., Lawlor, D. W. & Jeffers, W. deC. (1978). A drought experiment using mobile shelters: the effect of drought on barley yield, water use and nutrient uptake. *Journal of Agricultural Science, Cambridge* **91**, 599–623.

Fitter, A. H. & Hay, R. K. M. (1981). *Environmental Physiology of Plants.* London: Academic Press.

Jarrell, W. M. & Beverly, R. B. (1981). The dilution effect in plant nutrition studies. *Advances in Agronomy* **34**, 197–224.

Johnston, A. E. (1969). Plant nutrients in crops grown on Broadbalk. *Rothamsted Experimental Station, Report for* 1968 Part 2, pp. 50–62.

Johnston, A. E., Warren, R. G. & Penny, A. (1970). The value of residues from long-period manuring at Rothamsted and Woburn. V. The value to arable crops of residues accumulated from potassium fertilizers. *Rothamsted Experimental Station, Report for* 1969 Part 2, pp. 69–90.

Jones, J. B. (1982). Tracking as a technique for evaluating the nutritional status of plants. In *Plant Nutrition* 1982. *Proceedings of the Ninth International Plant Nutrition Colloquium.* Vol. 1 (ed. A. Scaife), pp. 51–60. Slough: Commonwealth Agricultural Bureaux.

Legg, B. J., Day, W., Brown, N. J. & Smith, G. J. (1978). Small plots and automatic rain shelters: a field appraisal. *Journal of Agricultural Science, Cambridge* **91**, 321–336.

Leigh, R. A. & Johnston, A. E. (1983). Concentrations of potassium in the dry matter and tissue water of field-grown spring barley and their relationships to grain yield. *Journal of Agricultural Science, Cambridge* **101**, 675–685.

Mengel, K. & Arneke, W-W. (1982). Effects of potassium on the water potential, the pressure potential, the osmotic potential and cell elongation of levels of *Phaseolus vulgaris. Physiologia Plantarum* **54**, 402–408.

Metson, A. J. (1956). Methods of chemical analysis for soil survey samples. *New Zealand Soil Bureau,* Bulletin No. 12.

Olsen, S. R., Cole, C. V., Watanabe, F. S. & Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *United States Department of Agriculture Circular No.* 939, p. 19.

Pitman, M. G. (1972). Uptake and transport of ions in barley seedlings. III. Correlation between transport to the shoot and relative growth rate. *Australian Journal of Biological Sciences* **25**, 905–919.

Pitman, M. G., Mowat, J. & Nair, H. (1971). Interpretation of processes for accumulation of salts and sugars in barley roots. *Australian Journal of Biological Sciences* **24**, 619–631.

Salt, P. D. (1968). The automatic determination of phosphorus extracts of soils made with 0·5-M sodium hydrogen carbonate and 0·01-M calcium chloride. *Chemistry and Industry*, 584–586.

Warren, R. G. & Johnston, A. E. (1967). Hoosfield Continuous Barley. *Rothamsted Experimental Station, Report for* 1966, pp. 320–338.

Wyn Jones, R. G., Brady, C. J. & Spiers, J. (1979). Ionic and osmotic relations in plant cells. In *Recent Advances in the Biochemistry of Cereals* (ed. D. L. Laidman and R. G. Wyn Jones), pp. 63–103. London: Academic Press.