

Nutrient uptake and export from an Australian cotton field

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Abstract Soil fertility may decline as a result of nutrient export from high-yielding cotton crops and this may limit the productivity of future crops unless these nutrients are replaced. Uptake of nutrients by cotton (*Gossypium hirsutum* L.) and nutrient export from the field in seed were measured within two cropping systems experiments from 1999 to 2005 in a flood-irrigated cotton field. Lint yields of the seven crops assessed ranged from 975 to 2725 kg lint/ha. Nutrient uptake was measured at mid to late boll-fill and nutrient removal determined from analysis of delinted seed. Cotton crops accumulated an average of 180 kg N/ha (range 67–403), 27 kg P/ha (range 18–43), 167 kg K/ha (range 88–264), 41 kg S/ha, 160 kg Ca/ha, 36 kg Mg/ha, 7 kg Na/ha, 890 gm Fe/ha, 370 gm Mn/ha, 340 gm B/ha, 130 gm Zn/ha and 51 gm Cu/ha. On average, the seed within harvested seed cotton removed 93 kg N/ha (range 38–189), 18 kg P/ha (range 8–34), 29 kg K/ha (range 13–51), 8 kg S/ha, 4 kg Ca/ha, 12 kg Mg/ha, 0.2 kg Na/ha, 136 g Fe/ha, 12 g Mn/ha, 41 g B/ha, 96 g Zn/ha and 20 g Cu/ha. Nutrients contained in the lint and trash were not included.

For crops yielding about 1800 kg/ha, 70% of the Zn and P taken up was removed in the seed, also 52% of N, 38% of Cu, 34% of Mg, 21% of S, 17% of K and Fe, 12% of B and only 3% of Ca, Mn and Na. Predictive equations were developed to allow growers to estimate the removal of nutrients given the lint yield measured from their cotton crops.

Keywords Fertility · Flood irrigation · Nitrogen · Nutrition · Phosphorus · Potassium · Micronutrient · Removal · Replacement

Introduction

Lint yields from Australian flood-irrigated cotton crops have increased steadily over the past 25 years; average yield for the 2004/05 season was 2040 kg lint/ha and in the previous 5 years averaged 1630 kg lint/ha, 2.6 times the world average (Cotton Australia, 2006). This increase can be attributed to cultivar improvement, better agronomic management such as permanent bed (minimum till) systems and increased crop water-use-efficiency (Constable et al., 2001). High-yielding cotton crops impose a high demand for mineral nutrients from the soil over a short period of time, and foliar nutrient deficiency symptoms can arise during crop maturity in high-yielding cotton crops as nutrients are

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rapidly translocated from the foliage into the developing bolls (Wright 1999). In many instances, cotton production is constrained by soil fertility and the crop's ability to accumulate nutrients (Dorahy et al. 2004). Producers can afford to apply chemical fertilisers to overcome nutrient limitations because of the high value of cotton lint.

Nutrient export escalates as yields increase and there is increased grower interest to maintain high soil fertility by applying equivalent amounts of macronutrients (NPK) to those removed in seed cotton. Hearn (1981), Constable and Rochester (1988) and Rochester et al. (2001c) have published estimates of nutrient export at various yield levels, making it possible for cotton growers to estimate nutrient removal when lint yields are known. While there is commonly no lint yield response to P or K application, applying these nutrients will arrest soil fertility decline and delay or avoid the onset of nutrient deficiencies. This constitutes a strategic change in nutrient management, as most growers preferred to apply nutrients only when there was a likely economic response to fertiliser application. Combining nutrient removal information with more traditional soil and tissue testing will ensure soil fertility and crop nutrition are maintained or improved.

Previous studies of nutrient uptake and export from various cotton cropping areas throughout the world have concentrated on N, P and K and over short periods of time and assessed at only a limited number of lint yields.

This research aimed to quantify the levels of all the important nutrients taken up by cotton and to determine the amounts of each nutrient removed in seed cotton over a wide range of yield levels over several years. This was achieved by monitoring an experiment designed to evaluate the interaction between N fertiliser application and various rotation cropping systems over a seven-year period. Crop nutrient uptake and the quantities of each nutrient exported from each field were both related to lint yield, to allow growers to gauge the quantities of nutrients taken up and removed from their fields.

Materials and methods

Experimental site

The field was situated at the Australian Cotton Research Institute, Narrabri, New South Wales, Australia (150°E, 30°S). The climate is subtropical; mean maximum temperature through flowering and boll-fill is 33.5°C (January–March); annual rainfall averages 645 mm but is highly variable (420 and 870 mm for first and ninth deciles). On average, 420 mm falls through the cotton season (October–April). The soil was a fertile alkaline dark greyish–brown cracking medium clay, classified as a fine, thermic, montmorillonitic Typic Haplustert (Soil Survey Staff, 1996). Soil pH was 7.9, EC 1.2 dS/m, organic carbon 1.3%, CEC 35 meq/100 g, and available P (Colwell bicarbonate-P) 61 mg/kg. Responses by cotton to fertilisers other than N and Zn have not been recorded at this site, despite irrigated cotton and wheat cropping for 25 years prior to this experiment. This field supports two concurrent cropping system experiments, as reported by Rochester et al. (2001a, b) and Rochester and Peoples (2005).

Cropping systems experiments

These two experiments aimed to monitor the various legume and cereal rotation crops and assess their effects upon the productivity of following cotton crops (Rochester and Peoples, 2005). These rotation treatments produced a wide range of soil fertility conditions that influenced crop nutrient uptake and lint yield. Rotation systems included annual and biannual cotton cropping, with or without cereal or legume rotation crops. In each experiment, the cropping systems constituted the main plots of a split plot design and the main plots were replicated four times. Each main plot was divided into subplots (16 m long and 8 × 1 m rows wide). Nitrogen fertiliser was applied as anhydrous ammonia at rates between 0 and 200 kg N/ha in increments of 25 kg N/ha. N fertilizer was applied in mid-September, 1 month before cotton was sown. Nutrient uptake, yield and export data were collected only from those plots that received 0, 100 or 200 kg N ha⁻¹. The data presented here

($n = 87$) are the means of the four replicates for each cropping system at each of the three N rates in each year. The N rates were re-randomised every 2 years. Where cotton or cereal was grown in the intermediate year (continuous cotton treatments), N fertiliser was applied prior to sowing at the optimum rate determined in the previous year. Zinc (1 kg $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}/\text{ha}$) was applied 1 month prior to sowing the cotton every second year.

Cotton agronomy and harvest

All crops were grown on 1 m spaced rows, which were maintained throughout the experimental period. Normally, the cultivar having highest yield potential was sown; hence, a different transgenic cotton cultivar was sown each year. Cotton was sown in mid-October each year. As rainfall is extremely variable in this environment, crops were flood-irrigated according to commercial practice and insects were controlled when they exceeded commercial threshold levels. Weeds were controlled with mechanical cultivation and herbicides.

Following chemical defoliation, the two central rows of each 8 row plot were mechanically picked and weighed and a subsample (~300 g) of seed cotton was ginned to determine lint yield.

Nutrient uptake and export measurements

Crop nutrient uptake was assessed at cut-out (mid to late boll-fill), about 130 days after sowing. Above-ground crop was removed from 1 m of crop row to determine crop dry matter (DM). A subsample (2–3 plants) was selected to determine nutrient concentration following drying at 70°C for 72 h in a forced-draught dehydrator. The material was milled and analysed for N by Kjeldahl digestion. All other nutrient concentrations were determined by ICP-AES analysis after acid digestion. Nutrient uptake was determined as the product of nutrient concentration and the mass of crop DM.

Fuzzy seed was acid-delinted with 98% sulphuric acid. Once the residual lint was removed from the seed coat, the seed was washed under running water for 2 min, dipped in limewater to

neutralise any residual acid and rinsed again under running water. The delinted seed was dried overnight at 70°C and then finely ground in a small mill capable of grinding oilseeds. The N content of the milled seed was determined by Kjeldahl digestion. All other nutrient concentrations were determined by ICP-AES analysis after acid digestion. Nutrient export was determined as the product of nutrient concentration and the mass of delinted seed. No allowance was made for the small quantities of nutrients contained in the trash and the cotton lint (Constable et al. 1988).

Statistical analysis

The SigmaPlot program (SPSS, 2000) was used to fit the nutrient uptake and nutrient removal data to lint yield data. The 95% confidence limits are indicated for the linear regressions in Figs. 1, 3 and 4.

Results

Nutrient uptake

Cotton crops accumulated an average of 180 kg N/ha (range 67–403), 27 kg P/ha (range 18–43), 167 kg K/ha (range 88–264), 41 kg S/ha, 160 kg Ca/ha, 36 kg Mg/ha, 7 kg Na/ha, 890 g Fe/ha, 370 g Mn/ha, 340 g B/ha, 130 g Zn/ha and 51 g Cu/ha (Fig. 1). The extent of this data covers the range of nutrient uptakes normally experienced in commercial irrigated cotton crops in Australia (Cotton Australia, 2006).

Concentrations of each nutrient in the plants varied over a relatively narrow range; mean nutrient concentrations (% or mg/kg) in crop DM and their ranges over the seven seasons are given in Table 1.

Uptake of each nutrient was significantly correlated with lint yield (Fig. 1). A linear regression model fitted all nutrients, with the coefficients of the regression equations shown in Fig. 1 given in Table 2. However, until a substantial plant has grown (> 1 t DM/ha) few bolls are produced or little lint harvested. Hence, all intercepts (“*a*” values) in Table 2 should be negative. Collecting

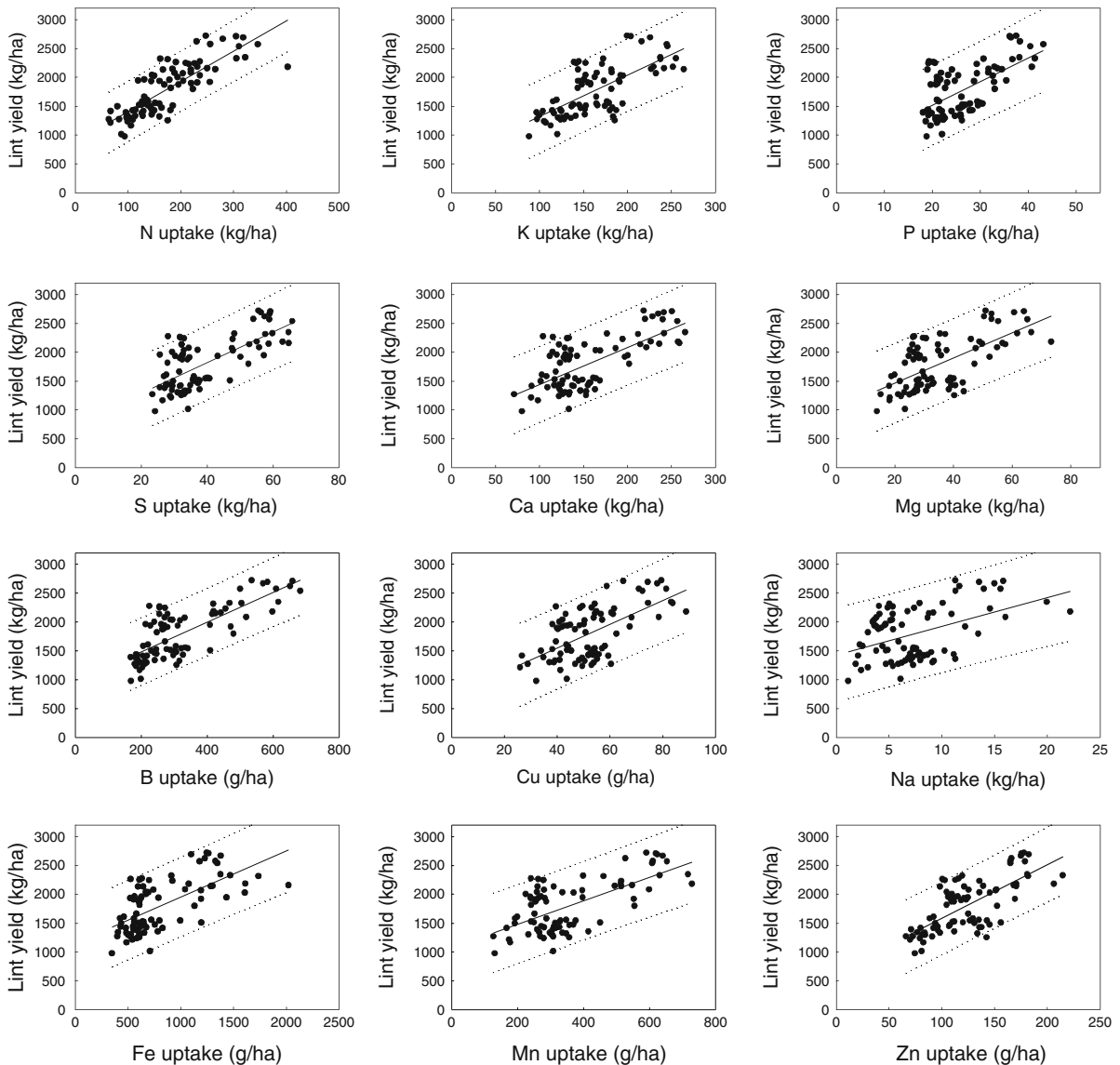


Fig. 1 The relationships between cotton lint yield and the uptake of each nutrient. The dotted lines represent the 95% confidence limits

further data from low-yielding crops with DM less than 5 t/ha may improve the accuracy and form of these regression equations.

Crop DM was significantly related to lint yield (Fig. 2). This relationship suggests that potential lint yield may be increased by increasing the biomass of the cotton crop if the length of the season allows this. A curvilinear model would make more sense biologically, with the curve bending more toward the origin, but this was not

significant over the range of this data. However, a quadratic model indicated that the curve reached maximum yield at about 20 t DM/ha. This confirms the higher nutrient uptake associated with higher lint yields (Fig. 1).

Nutrient export

On average, harvest of seed cotton removed 93 kg N/ha (range 38–189), 18 kg P/ha (range 8–34),

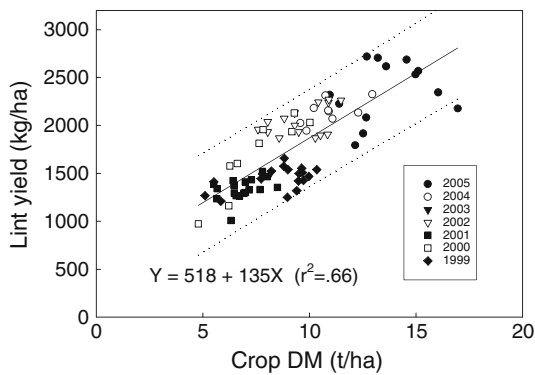


Fig. 2 The linear relationship between cotton crop DM and lint yield over a seven-year period. The dotted lines represent the 95% confidence limits

29 kg K/ha (range 13–51), 8 kg S/ha, 4 kg Ca/ha, 12 kg Mg/ha, 0.2 kg Na/ha, 136 g Fe/ha, 21 g Mn/ha, 41 g B/ha, 96 g Zn/ha and 20 g Cu/ha.

Nutrient export was firstly related to crop nutrient uptake (Fig. 3). There was a three-fold range in nutrient export over the 7 year period. Comparing the mean nutrient concentrations (Table 1) in the crop DM and in the delinted seed, indicates that N, P and Zn were more highly concentrated in the seed than in the crop DM; K, S, Ca, Fe, Mn and B were less concentrated in the seed than the crop DM and Mg, Na and Cu remained at a similar concentration in the seed and crop DM. The ranges of concentrations of each nutrient in the delinted seed was narrower than those found in the crop DM (Table 1) with the exceptions of Zn, which was similar, and P, which had a considerably wider range. Despite this variation, lint yield was the major factor determining quantities of nutrient exported.

To assess the relationships between nutrient uptake and nutrient export, a linear regression model was fitted to all nutrients (Fig. 3); the coefficients of the regression equations given in Table 3. The relationships were all statistically significant, except for sodium, as sodium exported was independent of sodium uptake.

The proportion of each nutrient exported in seed cotton relative to that taken up by the crop at cut-out is given in Table 4. The proportion of each nutrient exported is derived from the regression equations (Fig. 3) relating nutrient export in seed to nutrient uptake at cut-out. The regression equations (Figs. 1 and 4) are used to

describe the proportion of each nutrient exported relative to that taken up, at two yield levels. Relatively more of each nutrient taken up was exported in the smaller (lower DM and yield) crops. High-yielding crops took up more luxuriant amounts of each nutrient, compared with that exported. Importantly, about 71% of the P and 70% of the Zn taken up was exported, and 52% of the N taken up, but considerably less of the other nutrients. Very little Ca or Na was exported from the field.

Nutrient export was plotted against lint yield (Fig. 4). The regression equations derived from Fig. 4 are given in Table 5. All coefficients were statistically significant (at least $P < 0.01$) unless otherwise stated. The linear regression model most accurately fitted the data of each nutrient over the yield range (975–2725 kg/ha). These equations allow commercial growers to estimate nutrient export from fields based on their lint yield assessments following picking of their crops, over the range of lint yields determined in this experiment.

Discussion

There was a three-fold range in crop nutrient uptake, DM and nutrient export over the 7-year period, but a narrower range in nutrient concentration in crop DM and seed. Nutrient uptake was more strongly determined by crop DM than by nutrient concentration, and nutrient export was more strongly determined by yield than nutrient concentration in the seed.

Higher nutrient uptake was associated with higher lint yields (Fig. 1). In Australia, lint yields have increased steadily over the past 20 years (Hearn 1981; Cotton Australia 2006), as has nutrient uptake. This is in part attributable to cotton cultivar improvement (Constable et al. 2001), but also to improved insect pest control, agronomic management and soil fertility (Rochester and Peoples 2005).

Nutrient uptake

The quantities of nutrients taken up by cotton crops in various countries throughout the world

are comparable to those determined in this study, where yield levels are taken into account. With few exceptions, nutrient uptake data from other reports (Table 6) fitted within the confidence limits of the data presented in this study. Further, the data from the cited literature in Table 6 ranged from 5.3 to 18.8 kg N/100 kg lint, while the data from Fig.1 indicated that between 5.8 and 12.3 kg N/100 kg lint were taken up by cotton at the extremes of the yield range, possibly indicating that current high-yielding cultivars are

becoming increasingly N-efficient. Previous reports in Australia indicate crop N uptakes of 130 to 200 kg/ha for cotton yielding 1500 to 2600 kg lint/ha (Constable et al., 1992). Constable and Rochester (1988) showed close relationships between crop N uptake and lint yield. Duggan et al. (2006) reported an exponential function relating low lint yield (100–1500 kg/ha) with P uptake of 1–18 kg P/ha which both extends and corroborates the data of the present study. However, the P uptake reported by Wang et al. (2003)

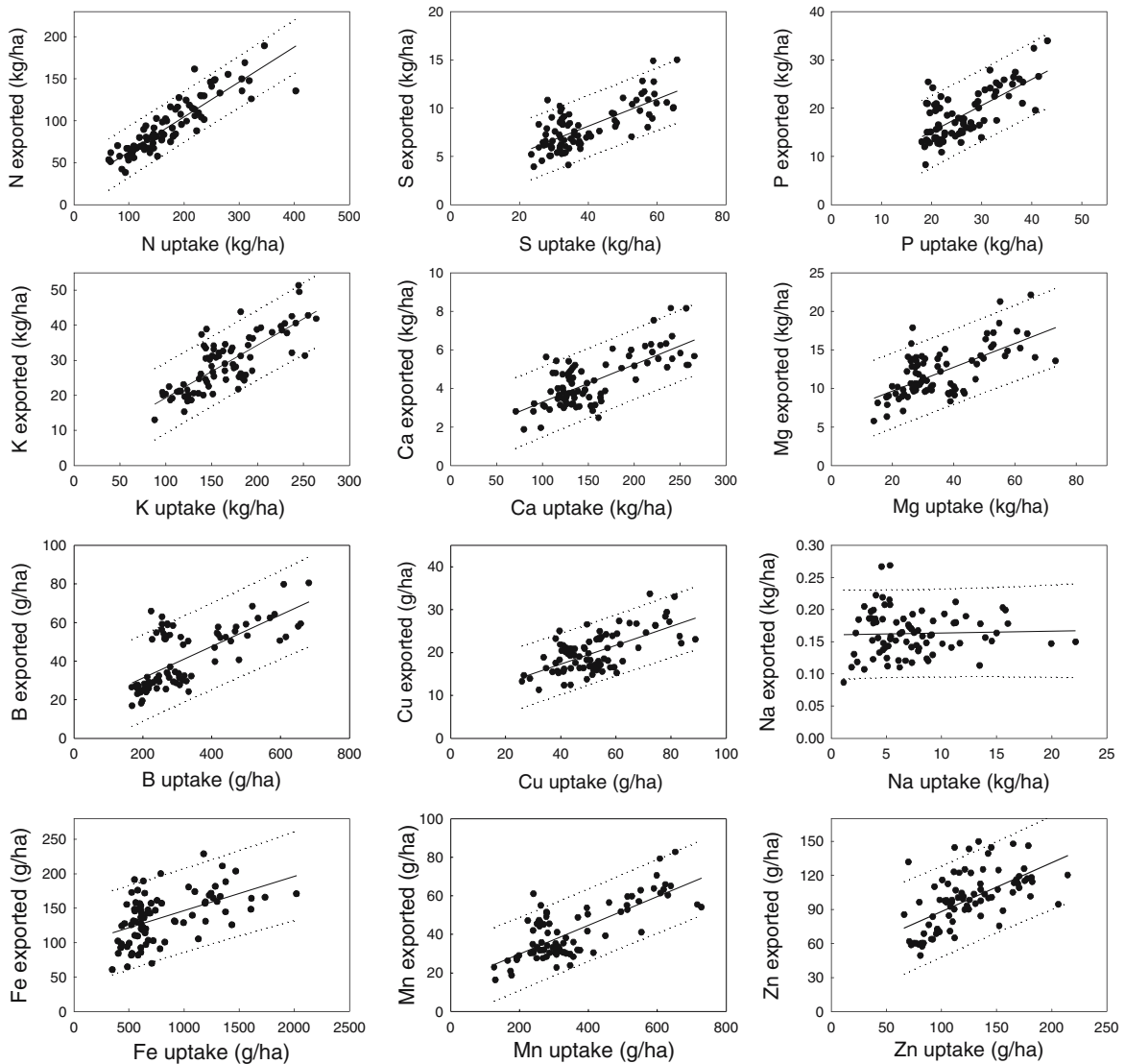


Fig. 3 Relationships between cotton crop nutrient uptake and the export of that nutrient in delinted seed. The dotted lines represent the 95% confidence limits

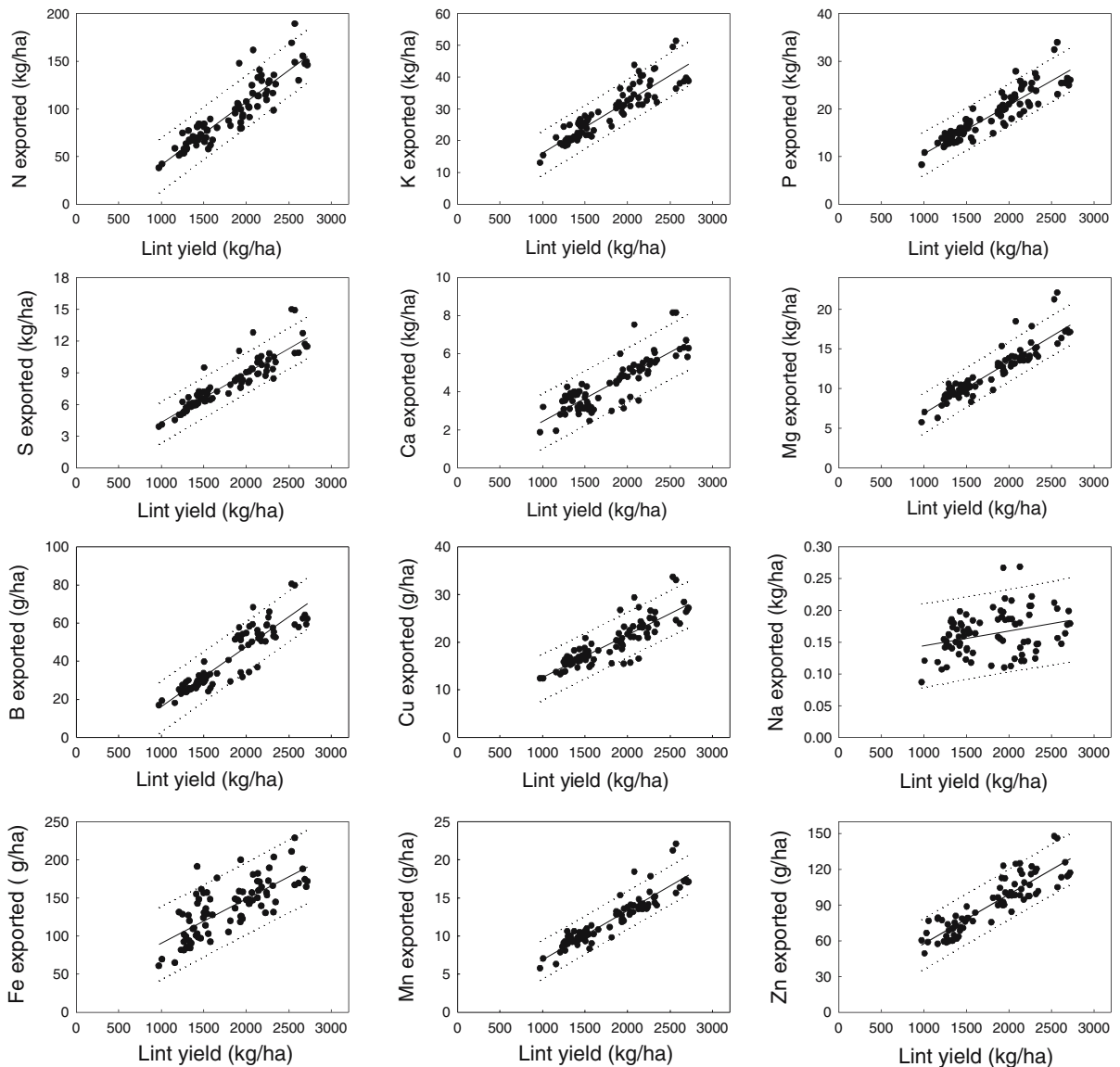


Fig. 4 The relationships between nutrient export in cottonseed and lint yield, which enable nutrient removal to be estimated from lint yields measured on commercial fields. Dotted lines represent the 95% confidence limits

is more than twice the maximum P uptake measured in Australian cotton, and is beyond the confidence limits depicted in Fig. 1.

The review by Hearn (1981) suggested that cotton will take up about 20 kg K/227 kg bale of lint produced. Similar K uptake/227 kg bale was observed in the present study in lower-yielding crops, but higher-yielding cotton took up about 25 kg K/227 kg bale of lint produced. Hearn

(1981) also indicated 14–33 kg Ca was taken up per 227 kg bale of lint produced, compared with about 25 in this study.

Mullins and Burmester (1993) quote values of 28, 626, 388 and 103 g/ha for Cu, Fe, Mn and Zn uptake, respectively for cotton grown in acid soils of Alabama USA; these values are close to those presented in this study except for higher zinc uptake, which probably reflects the higher Zn

Table 1 The mean and ranges of nutrient concentrations determined in crop DM at cut-out and delinted seed over the seven years of monitoring cotton crops within the experiment

	Crop DM		Delinted seed	
	Mean	Range	Mean	Range
Nitrogen (%)	1.75	1.09–2.43	3.34	2.56–4.08
Phosphorus (%)	0.30	0.22–0.41	0.67	0.56–0.84
Potassium (%)	1.89	1.52–2.37	1.05	0.97–1.1
Sulphur (%)	0.43	0.31–0.62	0.28	0.26–0.33
Calcium (%)	1.73	1.19–2.36	0.16	0.13–0.20
Magnesium (%)	0.38	0.26–0.53	0.43	0.39–0.52
Sodium (%)	0.08	0.03–0.14	0.06	0.04–0.09
Iron (mg/kg)	91	51–194	50	38–72
Manganese (mg/kg)	38	25–53	15	13–17
Boron (mg/kg)	35	24–47	15	13–17
Copper (mg/kg)	6.0	4.0–11.3	7.3	5.7–9.3
Zinc (mg/kg)	13.8	9.7–18.5	31	28–38

availability in acid soils. In comparison, Constable et al. (1988) reported mean values of 20, 600, 450 and 60 g/ha for Cu, Fe, Mn and Zn uptake, respectively, for 35 cotton crops grown on alkaline soils of northern NSW, Australia, values similar to those in the present study (Table 4). Mn uptake was considerably higher at some sites assessed by Constable et al. (1988) where the heavy clay soils may have been waterlogged during the growing season.

Table 2 The coefficients of the regressions of lint yield upon nutrient uptake at cut-out

	A	b	r ²
Nitrogen	882 (77)	5.24 (0.41)	0.67 ***
Phosphorus	695 (163)	41.0 (6.0)	0.37 ***
Potassium	600 (139)	7.18 (0.82)	0.49 ***
Sulphur	752 (129)	26.7 (3.0)	0.49 ***
Calcium	796 (121)	6.43 (0.75)	0.47 ***
Magnesium	1026 (106)	21.8 (2.8)	0.42 ***
Sodium	1427 (91)	49.6 (10.6)	0.21 ***
Iron (g/ha)	1148 (92)	0.80 (0.10)	0.42 ***
Manganese (g/ha)	1071 (99)	2.04 (0.26)	0.43 ***
Boron (g/ha)	969 (84)	2.57 (0.24)	0.58 ***
Copper (g/ha)	720 (154)	20.6 (2.9)	0.38 ***
Zinc (g/ha)	652 (128)	9.3 (1.0)	0.51 ***
Crop DM (t/ha)	519 (104)	135 (11)	0.66 ***

The equations take the form $Y = a + bX$, where Y is lint yield (kg/ha) and X is the nutrient uptake (g or kg/ha). Standard error of the coefficient is given in parentheses; $P < 0.01$ for all coefficients

Nutrient export

Hearn's (1981) review stated that around 60, 40 and 20% of N, P and K taken up was removed, compared with an estimated 52, 69 and 17% in this study for cotton yielding 1800 kg lint/ha (Table 4), typical for Australian cotton crops. This suggests a much higher importance of P nutrition in modern higher-yielding crops, especially as soil P fertility may have declined where removal has not been balanced with P fertiliser input or possibly, current cotton cultivars may translocate P from foliage to seed more efficiently than older cultivars. Importantly, the gross export of nutrients increases with yield, while the proportion of nutrients exported relative to those taken up decline substantially (Table 4). Prasad et al. (2004) quote values of 39, 6.2 and 32.8 kg N, P and K removed/t cottonseed, concurring with the values in Table 4 for N and P, but values are much higher for K. Thus, the N:P:K ratio given by these researchers (1.01:0.37:1) is at variance with the ratio 3.18:0.64:1 derived from Table 1, due to the higher K content of their seed.

In crops yielding 1180 to 1630 kg lint/ha, Bassett et al. (1970) measured export of 70, 11 and 21 kg/ha N, P and K respectively and noted that Na was largely excluded from the seed. Unruh and Silvertooth (1996) measured N, P and

Table 3 The coefficients of the regressions of nutrient export upon nutrient uptake at cut-out

	A	b	r ²
Nitrogen	19.1 (3.7)	0.42 (0.02)	0.81 ***
Phosphorus	4.24 (1.7)	0.54 (0.06)	0.47 ***
Potassium	4.15 (ns)	0.15 (0.01)	0.62 ***
Sulphur	2.49 (0.61)	0.14 (0.01)	0.52 ***
Calcium	1.34 (0.34)	0.02 (0.002)	0.52 ***
Magnesium	6.60 (0.75)	0.15 (0.02)	0.42 ***
Sodium	0.61 (0.01)	0.00 (ns)	ns
Iron (g/ha)	96.9 (8.1)	0.05 (0.01)	0.26 ***
Manganese (g/ha)	14.8 (2.7)	0.08 (0.01)	0.57 ***
Boron (g/ha)	14.9 (3.2)	0.08 (0.01)	0.49 ***
Copper (g/ha)	8.57 (1.55)	0.22 (0.03)	0.41 ***
Zinc (g/ha)	45.1 (8.2)	0.43 (0.06)	0.35 ***

The equations take the form $Y = a + bX$, where Y is nutrient export (kg/ha) and X is the nutrient uptake (g or kg/ha). Standard error of the coefficient is given in parentheses. All regressions, except for sodium, were statistically significant ($P < 0.001$) and the coefficients were all statistically significant (at least $P < 0.05$)

Table 4 The ranges of each nutrient taken up and exported and the proportion of each nutrient exported relative to that taken up by the crop at two yield levels, as derived from the regression equations presented in Figs. 1 and 4

	Uptake	Export	% Exported	
			1800 kg lint/ha	2400 kg lint/ha
Nitrogen (kg/ha)	64–403	39–168	52	46
Phosphorus (kg/ha)	18–43	14–28	69	60
Potassium (kg/ha)	43–264	17–88	17	15
Sulphur (kg/ha)	24–66	5.8–11.8	21	18
Calcium (kg/ha)	71–266	2.7–6.5	3	2
Magnesium (kg/ha)	13.9–73.3	8.7–17.9	34	25
Sodium (kg/ha)	1.1–22.2	0.16–0.17	2	1
Iron (g/ha)	350–2022	102–161	17	11
Manganese (g/ha)	127–729	6–22	3	2
Boron (g/ha)	168–682	26–65	13	11
Copper (g/ha)	26–89	14–28	38	31
Zinc (g/ha)	66–214	59–109	73	61

K export of 67, 11 and 26 in seed of a crop yielding 1328 kg lint/ha. The data from these reports all lie within the confidence limits of Figs. 1, 2 and 4.

Egelkraut et al. (2004) measured N concentrations ranging from 2.4% to 4.0% in cottonseed in several crops in Georgia USA; these concentrations are identical to those reported in Table 1. They also observed that seed N concentration increased linearly with N fertiliser rate even beyond that N rate at which lint yield was maximised. Hence, N fertiliser applications in excess of that required to optimise lint yield should enhance the N concentration in the cottonseed and increase the protein content of this product. However, excessive N applications

Table 5 The coefficients of the regressions of nutrient export upon lint yield

	<i>a</i>	<i>B</i>	<i>r</i> ²
Nitrogen	–1 (6.2)	0.0663 (0.0034)	0.82 ***
Phosphorus	0.34 (ns)	0.0102 (0.0005)	0.81 ***
Potassium	–0.27 (ns)	0.0163 (0.0008)	0.82 ***
Sulphur	–0.36 (ns)	0.0047 (0.0002)	0.83 ***
Calcium	0.02 (ns)	0.0024 (0.0002)	0.70 ***
Magnesium	0.39 (ns)	0.0065 (0.0003)	0.84 ***
Sodium	0.12 (0.01)	0.0000 (0.0000)	0.09 **
Iron (g/ha)	32.3 (10.7)	0.0583 (0.0058)	0.55 ***
Manganese (g/ha)	0.39 (ns)	0.0065(0.0003)	0.84 ***
Boron (g/ha)	–15.4 (3.0)	0.0315 (0.0016)	0.82 ***
Copper (g/ha)	3.68 (1.1)	0.0089 (0.0006)	0.74 ***
Zinc (g/ha)	15.8 (4.6)	0.0415 (0.0025)	0.78 ***

The equations take the form $Y = a + bX$, where Y is nutrient export (g or kg/ha) and X is lint yield (kg/ha). Standard error of the coefficient is given in parentheses; $P < 0.01$ for all coefficients

reduce the profitability of cotton production and promote environmental problems due to gaseous N losses or groundwater contamination.

Dorahy et al. (2004) found that two-thirds of the P taken up was exported (15 kg P/ha) from commercial Australian cotton crops, which conforms to the lower yielding crops of the present study. Hearn (1981) suggested that P removal of 2.7 kg/227 kg bale of lint produced (range 1.8–4.0) was representative of the data he compared, slightly higher than the 2.3 kg/bales in the higher yielding crops here. More similar to the values presented in Table 1, Singh and Kairon (2001) determined P content of cottonseed (0.55–0.61%).

Singh and Kairon (2001) determined the S content of cottonseed increased from 0.30% to 0.72% where S-fertilisers were applied; S application resulted in yield increases of up to 23%. These levels are significantly higher than those of the present study, hence, S nutrition at this study site will be investigated in the future.

Mullins and Burmester (1993) report values of 8, 88, 23 and 49 g/ha for Cu, Fe, Mn and Zn export, respectively, for rain-grown cotton grown in Alabama USA; these values are about half those determined in this study. In comparison, Constable et al. (1988) measured export of 21, 460, 84, 147 and 91 g/ha for Cu, Fe, Mn, B and Zn, respectively, in fuzzy seed from flood-irrigated Australian cotton crops, values similar to those for Cu and Zn in the present study, but considerably (2 to 3 times) higher for Fe, Mn and B. These differences could be related to soil type and possibly to poor soil structure and waterlogging, factors that were more

Table 6 Reported values of N, P and K uptake (kg/ha) with the lint yield (kg/ha) and crop DM produced (t/ha)

Reference	N	P	K	Yield	Crop DM
Janat (2004)	417			2221	
Dorahy et al. (2004)		22			
Wang et al. (2003)	250–386	38–107	285–283	2000–3000	
Srinivasan (2003)	98	17	97	1834	7.7
Nadanassababady and Kandasamy (2002)	145	34	133	1248	
Unruh and Silvertooth (1996)	201	31	254	1328	
More and Agale (1993)		33		1627	4.9
Constable et al. (1992)	130–200			1500–2600	
Mullins and Burmester (1990)	128	17	106	1000	8.0
Halevy (1976)	230	45	174	1700	12.8
Basinski et al. (1975)	280			1800	
Bassett et al. (1970)	142	19	127	1405	

Those values beyond the confidence limits derived from this study are given in italics

common in some soils in the time that Constable et al. (1988) surveyed cotton crops. The lower B removal in the present study may be due to the lighter soil (lower clay content and hence possible leaching of mobile nutrients such as B after 30 years of flood irrigation) compared with the majority of cotton-growing soils. The difference in nutrient removal between the two studies can be attributed to the differences in seed nutrient concentrations.

Although Zn and P are considered relatively immobile in the soil, the mobility of N, Zn and P within the plant is noteworthy (Table 4). As the cotton plants matured, most of these nutrients that had accumulated in the foliage were translocated to the seed. Cotton crops grown in Australia are known to be well infected with VAM fungi from the seedling stage that assist with nutrient uptake (D. Nehl, pers. comm.; Rich and Bird 1974).

Calculating nutrient export and nutrient replacement strategy

Most cotton growers measure their lint yields accurately on a field-by-field basis, especially where yield monitors have been mounted on cotton pickers. This enables ready estimation of nutrient export according to Fig. 4 or using the equations presented in Table 5, where yields lie between 975 and 2,725 kg lint/ha. Based on this knowledge, commercial cotton growers can formulate their fertiliser program in accordance with the quantities of nutrients exported from each field and replace those nutrients that may limit

production. The macro-nutrients N, P, K and S are the most obvious nutrients to be replaced, but N fertiliser rates are determined by soil nitrate content assessed before sowing. Calcium is normally the dominant cation in these soils and may be replaced in the gypsum or lime that some growers apply. Magnesium is also highly abundant in these soils and replacement is not recommended. Sodium is taken up in large quantities by cotton crops growing in soils that contain more than 6% of their cations as sodium, but only traces are exported in seed cotton.

The micro-nutrients normally pose few problems in these soils, with the exception of zinc, which is normally replaced by applying zinc sulphate at 1 kg/ha every one to five years. No response to copper has been reported, although boron may be leached down the soil profile, especially in wet years (Katyal et al. 2004).

Some cotton growers who regularly achieve high yields now aim to maintain soil fertility by replacing the macronutrients removed in each crop, even though there may be no economic response to those applications, to help avoid future crop nutritional problems. Traditional soil and plant tissue analyses remain the basis for fertiliser recommendations as they indicate where responses to fertilisers are likely, while crop removal data suggest amounts of macronutrients required to maintain soil chemical fertility. This study also highlights the need for further research on several nutrients within the Australian cotton industry if soil fertility and high levels of production are to be maintained. Within the field

experiment studied, zinc, boron and sulphur in particular, appear to be in lower concentration in plant material than reported in other studies and require further study.

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