Final report
FREP Project 06-0626

Development of practical fertility monitoring tools for drip-irrigated vegetable production

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Executive summary:

Nutrient uptake and partitioning in drip-irrigated processing tomatoes was studied by conducting fertigation trials at UC Davis (UCD) and monitoring 6 commercial fields in the Sacramento and San Joaquin Valleys through the production seasons of 2007-08. At UCD deficient, adequate and excessive amounts of N and P fertilizer were compared, the P applied preplant and the N fertigated through the drip irrigation system. Every 2 weeks (UCD) or approximately every three weeks (commercial fields) whole plants were harvested for determination of crop biomass and macronutrient content. Concurrently, a range of soil and plant tissue samples were collected for determination of soil nutrient availability and crop nutrient status, with the aim of comparing the value of the various monitoring techniques in guiding fertility management.

Total fruit yields ranged from 45-71 tons/acre, and crop dry biomass ranged from 7,200-14,400 lb/acre. The four highest yielding sites (2 commercial fields and both UCD trials) averaged 64 tons/acre total fruit yield; those sites averaged a seasonal uptake of 249, 39 and 347 lb N, P and K per acre, respectively. In those high-yield fields nutrient uptake peaked 9-11 weeks after transplanting (between full bloom and first red fruit growth stage) at approximately 35, 4 and 40 lb per acre per week. A seasonal N application rate of 200 lb/acre or less (depending on residual soil NO_3-N availability) was adequate to support high-yield production. Concentrating N fertigation between early bloom and first red fruit growth stages matches the crop growth pattern; more than 70% of seasonal crop nutrient uptake occurs between these growth stages.

In-season nutrient monitoring via soil sampling, whether by suction lysimetry or collection of soil cores, proved to be problematic. NO_3-N concentration was highly stratified within the soil zone wetted by the drip tape, making a collection of a truly representative sample difficult. Also, in a management scheme in which multiple N applications are made throughout the rapid growth phase of the crop, only a modest level of soil NO_3-N must be maintained between fertigations. Regarding tissue monitoring, existing whole leaf total N, P and K sufficiency standards were found to be generally appropriate, whereas existing petiole sufficiency standards were found to be generally higher than required for high-yield production. The nutrient management practices of the cooperating growers appeared to be efficient with regard to N, but both P and K fertilization practices were inadequate to sustain both high yield production and soil fertility levels.

Introduction:

The conversion to drip irrigation is revolutionizing the California processing tomato industry; at the current rate of conversion more than half the acreage will be drip-irrigated within 5 years. This has important ramifications for fertility management. The higher yield potential, and the ability to respond to changing nutrient demands, makes more intensive nutrient monitoring in drip culture both useful and economically justifiable.

Optimizing nutrient management with drip irrigation will require both a detailed knowledge of crop nutrient uptake patterns, and the ability to monitor and interpret in-season nutrient status in both soil and crop. Currently, insufficient data is available on crop nutrient uptake by growth stage for this important crop under high yield, drip-irrigated conditions. Nutrient monitoring has historically centered on preplant soil testing, and in-season whole leaf or petiole analysis. With the advent of widespread drip irrigation there is interest in exploring other approaches such as soil solution monitoring, or petiole sap analysis (for both macro- and micronutrients). Unfortunately, recent research from around the country has cast doubt on the reliability of these analytical tools as in-season fertigation guides. This project was undertaken to develop accurate nutrient uptake and partitioning data for processing tomatoes under high yield drip-irrigated conditions, and to provide a critical assessment of a range of crop and soil nutrient monitoring options.

Objectives:

a) develop crop nutrient uptake and partitioning curves for drip-irrigated processing tomato across a range of field sites, and
b) evaluate and calibrate practical soil and plant monitoring tools to guide fertility management

Methods:

UC Davis trials

A drip-irrigated processing tomato trial was conducted at UC Davis (UCD) in both 2007 and 2008. In both years the preceding crop was field corn. In each year four fertility regimes were compared:

1) deficient N fertility
2) deficient P fertility
3) adequate N and P fertility
4) excessive N and P fertility

P fertility was manipulated by varying the preplant P application from 0 to 140 lb P_2O_5/acre. Preplant P (8-24-0) was placed in a single band in the plant row, approximately one inch below the transplant ball. N fertility was manipulated by applying varying amounts of UN-32 through the drip tape. Nine weekly fertigations were made in 2007, 8 in 2008; in both years fertigation was initiated at early bloom, and terminated around the time the early fruit began to ripen.

In both years the experimental design was a split plot within a randomized complete block. Fertility regime was the main plot, cultivar (AB2 or Heinz 9780) the split plot; there were three replications. Each split plot was three 60-inch beds wide and 100 feet long. Plots were transplanted on 9 May and 28 April in 2007 and 2008,

respectively. The transplants were established with sprinklers, then irrigated with a buried drip system; drip irrigation tape was placed approximately 8 inches deep in the bed centers. Drip irrigation was applied three times a week for the first month of irrigation, and daily thereafter. Irrigation volume was based on reference evapotranspiration (ET_o) and the degree of canopy cover. Seasonal drip application was 15.2 inches in 2007 and 19.7 inches in 2008.

Beginning approximately 5 weeks post-transplant (early flower growth stage) the plots were intensively sampled every two weeks. In each split plot 4 representative whole plants were harvested for measurement of total above-ground biomass, and macro- and micronutrient content; once fruit began to develop, the whole plants were segregated into vine and fruit samples. Additionally, approximately 30 recently matured whole leaves per split plot were collected between 7-10 AM. Eight leaves from each split plot were placed in a pressure bomb with multiple chambers; the chambers were pressurized to 10 bars (150 PSI), and the xylem solution exuded from the cut ends of the leaves was collected. To ensure adequate xylem volume for analysis these leaves were collected from plants that had been covered with an aluminized plastic mulch film for 30-60 minutes to bring the water potential of the leaves close to stem water potential. After removal from the pressure bomb these whole leaves were oven-dried for total nutrient analysis. From the remaining leaves in each sample the blade tissue was removed; half of the petioles were oven-dried, and the rest were crushed in a hydraulic press to provide a fresh sap sample. The following measurements were made on these plant samples:

1) vine and fruit dry weight
2) vine, leaf and fruit N, P, K, and micronutrient concentration
3) dry petiole NO_3-N, PO_4-P and K
4) petiole sap total N, NO_3-N, PO_4-P, K
5) petiole xylem total N, NO_3-N, PO_4-P, and K concentration

Soil sampling was conducted concurrently with the plant sampling. A suction lysimeter was installed in each subplot, with the collection cup located 9-15 inches deep, 4-6 inches from the drip tape. This placement was chosen to represent the concentrated root zone wetted by the drip tape. On each sampling date a vacuum was drawn and a sample of soil solution collected. From each split plot 6 soil cores taken from 6-15 inch depth, 4-6 inches to the side of the drip tape, were collected; the samples were blended, extracted with KCl, and analyzed for NO_3-N. N fertigation was done on Fridays, and all soil sampling was done between Tuesday and Thursday, so in all cases one or more irrigations occurred between fertigation and sampling. The soil solution samples were analyzed for NO_3-N, PO_4-P and K.

Plant and soil sampling was continued until 7-10 days before commercial harvest stage, at which point > 80% of fruit were red. At that point crop senescence is sufficiently advanced that additional nutrient uptake would be minimal, and loss of leaf tissue and early-ripening fruit could complicate biomass sampling. On the final sampling date (approximately 15 weeks after transplanting) fruit yield from 8 plants was measured to ensure accuracy.

All analysis was done by the UCD Analytical Lab. Laboratory procedures used are given on their website (http://danranlab.ucdavis.edu/).

Commercial field trials

In each of the 2007 and 2008 seasons three commercial drip-irrigated processing tomato fields were monitored. In 2007 those fields were located in the Sacramento Valley, in 2007 in the San Joaquin Valley. Site characteristics, transplant dates, cultivars used and grower nutrient management information are given in Table 1. In each field three locations were selected, and plant and soil sampling was performed as outlined for the UCD trials. Sampling was done 4 times over the season in each field in 2007, and 5 times in 2008.

Results:

Crop growth, yield and nutrient uptake

At UCD crop biomass, nutrient uptake and fruit yield was significantly higher in 2008 than in 2007 (Table 2). AB2 was significantly more vigorous and higher yielding than H 9780. The treatment defined as adequate N and P gave statistically equal growth and fruit yield compared to the excessive fertilizer treatment, in which an additional 103 lb N and 70 lb P_2O_5/acre was applied. Both the deficient N and deficient P treatments reduced fruit yield, but only the deficient N treatment significantly reduced crop biomass at harvest. To put the total fruit yields in perspective, typically about 90% of total yield is marketable, meaning that marketable yield in the 'adequate' treatment averaged > 55 tons/acre across cultivars and years. The only fruit quality effect was the influence of year on fruit color; at the final sampling in 2007 the fruit were less mature than in 2008.

Fertility treatment had a major impact on crop nutrient uptake. The low N treatment, with an average seasonal N application of 92 lb/acre, averaged 175 lb biomass N/acre at harvest; the growth restriction due to limited N supply reduced P and K uptake as well. By comparison, the adequate fertility treatment averaged 235 lb N/acre uptake on 187 lb N/acre mean fertilizer application. The excessive fertility treatment did increase crop N and P uptake considerably, but with no statistically significant yield advantage. Nutrient uptake followed a similar pattern in both years (Fig. 1). In the 5 weeks between transplanting and the first plant sampling crop growth rate was slow, with crop uptake of less than 30 lb N/acre over that period. Growth and nutrient uptake accelerated thereafter, with the next six weeks accounting for roughly 60% of seasonal crop biomass development and 80% of seasonal N uptake. Over that 6 week period about 70% of seasonal P and K were taken up.

It is constructive to compare how N and P deficiency had different effects on crop nutrient uptake (Fig. 2). The deficient and adequate N treatments showed roughly equivalent growth and N uptake through week 7 (early fruit set), with the deficient N treatment falling further behind as the rapid growth phase proceeded. Conversely, the P deficient treatment showed poor initial growth, but then nearly caught up with the adequate N treatment in both biomass and P uptake by harvest time. These differences suggested that soil P limitation occurred early in the season, before the root system could efficiently mine the soil profile, while N availability became limiting when crop growth rate reached its peak.

Partitioning of dry weight and N between vine and fruit is shown in Fig. 3. Once fruit development began vine growth slowed, with vine dry weight declining as the fruit became the primary 'sink' into which the plant directed both carbohydrates and nutrients.

By harvest the fruit accounted for more than 60% of the plant dry weight and > 70% of biomass N; the distribution of P and K were similar.

Seasonal N fertilizer rates were relatively consistent among the commercial fields, and bracketed the 'adequate' fertility treatment at UCD (Table 1). P fertilization of the commercial fields was quite conservative, averaging only 45 lb P_2O_5/acre. K fertigation was only done in the Sacramento Valley trials, and at low seasonal rates. The commercial fields had total fruit yields ranging from 45-71 tons/acre (Table 3); assuming marketable yield was 90% of total fruit yield, marketable yields in these fields ranged from approximately 41-64 tons/acre. Plant vigor varied widely among fields, ranging from 7,200-14,400 lb dry biomass/acre; fruit yield was positively correlated to biomass production (r = 0.92).

With the exception of field 6, which was extraordinarily vigorous, seasonal crop nutrient uptake in the commercial fields ranged between 183-245 lb N and 27-35 lb P per acre. Seasonal K uptake varied more widely, from a low of 159 lb/acre (field 1) to 297 lb/acre (field 4). With little or no K fertilization in all fields, the importance of soil K availability to crop K uptake was obvious; the correlation between crop K uptake and exchangeable soil K was r = 0.94. Dry matter and nutrient partitioning was similar to the UCD trials, with the majority of dry matter and nutrient content at harvest in the fruit in all fields.

In all fields crop N uptake exceeded the fertilizer rate, in some cases by a substantial amount; biomass N at harvest exceeded the seasonal fertilization rate by 127 lb/acre in field 6, and 79 lb N/acre at UCD in 2008. This suggests that a) processing tomato is an efficient crop at recovering N from the soil, and b) in the fields and in the rotations in which tomatoes are grown there is significant residual nitrogen availability and/or mineralization of soil organic N.

To mathematically describe macronutrient uptake, crop nutrient uptake data from the four highest-yields fields (commercial fields 3 and 6, and both UCD trials) were combined, and a polynomial regression line fit to the data; the nitrogen regression is shown in Fig. 4. Based on that equation, and similar ones for P and K, the predicted weekly crop uptake was calculated (Fig. 5). Nutrient uptake in these high-yield fields peaked between 9-11 weeks after transplanting (between full bloom and first red fruit growth stage) at approximately 35 lb N, 4 lb P and 40 lb K per acre per week.

This analysis provided the basis for a general N fertigation template (Table 4). Fertigation should be timed to stay ahead of the N uptake curve. In a worst-case scenario of a field with minimal residual N availability and minimal soil N mineralization potential, the fertigation rates listed should be adequate to support high-yield production. Rates lower than those listed would be appropriate in cases where significant residual soil N was present. Seasonal N rates of 200 lb/acre or less should be adequate under most field conditions. If N supply has been adequate to maximize vine growth and fruit set through early fruit ripening, no additional fertigation should be required to finish out the crop; the N present in the vine should be sufficient to support the developing fruit.

Regarding appropriate K fertigation management, it can be challenging to determine whether K fertigation is required in any particular field. The higher yield expectations and the more limited root zone from which to draw mean that the soil K availability threshold is higher with drip irrigation than with furrow irrigation. Prior processing tomato research in drip-irrigated fields showed that fields with exchangeable

soil K < 150 PPM are likely to be K-limited, and fields with soil K up to 250 PPM may respond to K fertigation, particularly where K makes up less than 2% of cation exchange (on a milliequivalent basis). Where K fertilization is appropriate, fertigation during fruit set will be the most effective application technique. Even in soil of limited K availability tomato plants can usually take up enough K to support early vine growth, but when fruit set begins crop uptake quickly exceeds the soil supply; the result is that the vine is stressed to maintain the developing fruit, and later-setting fruit are aborted. Concentrating K fertigation during fruit set minimizes this vine stress and maximizes fruit set. There is limited research information on K fertigation rates. Fruit K content at harvest is typically 200-250 lb/acre (240-300 lb K_2O equivalent), so application rates less than that represents 'mining' of soil K. However, on the basis of maximizing the economic return on the current crop, the first 100 lb K_2O/acre would probably achieve most of the potential yield benefit; the economic return on additional fertigated K would decline.

Soil sampling and diagnosis

Interpretation of soil NO_3-N monitoring data proved to be problematic. Analysis of standard soil cores collected from 6-15 inch depth, 4-6 inches from the drip tape (a location chosen to represent the primary root zone wetted by the tape), showed a trend in NO_3-N concentration that generally reflected the N fertigation treatments (Fig. 6). Soil NO_3-N in the excessive N treatment remained at or above 10 PPM through early red fruit stage (11 weeks after transplanting), while the adequate N treatment had soil NO_3-N below that level at all sampling dates except the initial sampling in 2008. However, soil NO_3-N was similar between the adequate and deficient N treatments at most sampling dates, making it impossible to delineate a 'sufficiency' or 'deficiency' level.

Stratification of NO_3-N within the root zone was another confounding factor for in-season soil sampling. Table 5 shows soil NO_3-N concentration by root zone location for the excessive N treatment in early July, 2008. NO_3-N differed by more than 100% among locations within the area wetted by the drip tape. Collection of a truly representative sample would be time-consuming, and complicated by the need to avoid damaging the buried drip tape. Uneven NO_3-N distribution within the wetted root zone makes the use of suction lysimeters especially problematic. Fig. 7 shows the relationship between soil solution NO_3-N collected by suction lysimetry and concurrently measured NO_3-N of composite soil samples drawn from the same location in the soil profile; each data point represents the value from a single lysimeter regressed against the soil NO_3-N of a blended sample of 6 soil cores collected within the same subplot. Although statistically correlated, the relationship was so tenuous as to make the lysimeter value completely unreliable. Even when averaged across the three replicate plots representing the same fertility treatment the relationship between soil solution sampling and analysis of soil cores was still highly variable.

With regard to soil solution PO_4-P monitoring there was a high degree of variability seen. In comparing PO_4-P values among lysimeter samples from the adequate P treatment at UCD the coefficient of variability within sample dates exceeded 50%. Soil solution K concentration was more stable, and at UCD showed a consistent pattern over time (Fig. 8). K concentration declined substantially from week 5 to week 7, the period corresponding to the start of the rapid growth phase of the crop. From that point forward

K concentration remained reasonably stable. In comparing the UCD data with that of the commercial fields at full bloom growth stage (during the rapid growth phase) it is clear that large differences existed, which were predictable based on the soil exchangeable K levels (Fig. 9). The importance of crop growth rate on soil solution K can be inferred from these data. Field 1 had low vigor and low yield, and higher soil solution K than fields with similar soil exchangeable K. At UCD soil solution K was lower in 2008 despite higher soil exchangeable K, apparently due to the higher crop K uptake rate by the more vigorous crop that year.

Tissue sampling and diagnosis

To evaluate the tissue nutrient monitoring data generated in this project it is useful to first consider the xylem and sap monitoring data from the 2008 UCD trial (Fig. 10). Xylem solution (the fluid carrying N from the roots to the vine in the transpirational stream) was initially high in all N treatments and declined over time. At the 5 week sampling date NO_3-N made up approximately 50% of total N in xylem, and that percentage declined thereafter. NH_4-N averaged less than 10% of total N at all sampling dates, meaning that organic N forms comprised approximately 40-50% of total xylem N from 5-11 weeks. Since the vast majority of N is taken up from the soil in NO_3^- or NH_4^+ form, these data suggest there is significant conversion of mineral N to organic N forms in the roots. Factors affecting the rate of this conversion could confound the use of tissue NO_3-N concentration as an N diagnostic.

Total N concentration in petiole sap was approximately 10 times that in xylem solution (Fig. 10). Across N treatments NO_3-N constituted > 70% of total N in weeks 5 and 7, but declined thereafter in the deficient and adequate N treatments, dropping below 40% by week 11. Again, these changing fractions of total N represented by NO_3-N over time and among N treatments call into question the use of sap NO_3-N as a diagnostic.

Fig. 11 shows the correlation of petiole sap NO_3-N, PO_4-P and K with dry petiole analysis. While all correlations were statistically significant, as a practical matter there is considerable scatter in the data, undoubtedly due in considerable part to differences in fresh petiole moisture content; differences in plant water status at the time of sample collection, or water loss before or during sap processing, would change the relationship between tissue fresh and dry values. It is important to note that both sap and dry petiole analysis was done with conventional laboratory equipment; the use of the 'Cardy' meter to analyze sap concentrations would introduce another significant source of variability.

Current UC tissue nutrient sufficiency guidelines were applied to tissue samples from the UCD trials (Fig. 12), and the commercial fields (Fig. 13, 14 and 15). The whole leaf guidelines used here were developed from a large-scale field survey (Hartz et al., 1993), in which sufficiency guidelines were calculated from the typical values of nutritionally balanced, high-yield fields. The petiole guidelines were taken from Ludwick (2002). The UCD data generally confirmed the validity of the existing whole leaf guidelines. The excessive and adequate treatments were comfortably sufficient for leaf N throughout the season, and for leaf P until week 11 (early red fruit stage, at which point fruit set had concluded and the heavy fruit load was drawing nutrients from the leaves). The deficient N treatment dipped below the sufficiency guidelines by week 9 (full bloom stage), corresponding to the time when the crop growth rate of the deficient and sufficient treatments began to diverge (Fig. 2). The deficient P treatment was at the

leaf sufficiency guideline at the initial sampling date (week 5, early flower) and considerably below the adequate treatment, but recovered to converge with the adequate treatment by week 9. As indicated in Fig. 2, growth and P uptake limitation in the deficient P treatment was an early season phenomenon; the ideal time to identify P limitation may be earlier than 5 weeks post-transplant.

Petiole NO_3-N remained high in the excessive N treatment, but dropped below the sufficiency value by week 7 in the deficient treatment. The adequate N treatment dropped below the sufficiency level by week 9, calling into question that late-season sufficiency value. Similarly, both the adequate and the excessive treatment were below the PO_4-P sufficiency level by week 9. No data on tissue K are presented for UCD since there were no K treatments applied, and the high soil K levels in both years gave uniformly high tissue K concentrations.

To fairly compare the commercial field data across the array of years, locations and planting dates it was necessary use growing degree days (GDD) in lieu of days after transplanting; GDD was calculated from CIMIS daily air temperature using 45 and 86 F as the low and high thresholds, respectively. Several of the commercial fields showed low early season leaf N, but with the exception of field 4 all fields exceeded sufficiency standards for the rest of the season (Fig. 13); the 4.6% sufficiency standard at early flower growth stage from Hartz et al. (1993) was apparently higher than required for maximum early growth. As the UCD data suggested, current petiole NO_3-N sufficiency guidelines are clearly higher than necessary, particularly after fruit set begins; only 1 of the 6 fields maintained petiole NO_3-N above the current guidelines throughout the season.

Regarding crop P status, 3 fields (#1, 2 and 4) began the season with low leaf P, with fields 1 and 2 near or below sufficiency throughout the season (Fig. 14). All three fields had moderate to low soil test P, and low P fertilization rates. In fact, P fertilization rates were generally modest across the commercial fields. P removal in fruit from the high yield fields averaged the equivalent of 70 lb P_2O_5/acre; only field 3 received that much P fertilization. Higher P fertilization rates are justified, particularly in fields with low P level (<15 PPM Olsen P). However, the current petiole PO_4-P guidelines are clearly higher than required. Only one field (#6, with a soil test level of 29 PPM) met the guidelines at any stage.

Three fields (#1, 2 and 5) were at or below early season leaf K guidelines. These fields had low to moderate exchangeable soil K (114-182 PPM), and little or no K fertilization. The general lack of K fertilization in these fields suggested that more attention to K requirements is warranted; only field 6 had soil K high enough to assure peak production. With high-yield tomato production removing the equivalent of >300 lb K_2O/acre with the fruit, soil K reserves in the confined rooting zone characteristic of drip irrigation can be drawn down relatively quickly. It was also clear that the existing petiole K standards are higher than appropriate, in that all fields were below the guideline at one or more sampling dates.

Whole leaf micronutrient concentrations are given in Table 6, together with deficiency levels from two existing sources. There were wide ranges in micronutrient concentrations among fields. In some cases that was the result of individual field differences (Mn and B, for example); in other cases regional factors (higher Ca and S at San Joaquin Valley sites vs. higher Mg at Sacramento Valley sites) were apparent. All

fields were comfortably above deficiency levels for all nutrients, and therefore there was no basis upon which to modify existing deficiency standards.

Combining the data generated in this project with that from other recent studies, revised tissue nutrient sufficiency guidelines are proposed in Table 7. These guidelines are expressly intended for drip-irrigated culture, in which multiple fertigations of N (and K at some sites) are made through the rapid growth phase of the crop. Furrow-irrigated fields in which in-season fertilization is managed solely by early sidedressing may require higher early season tissue nutrient concentrations. As with any proposed sufficiency standards these must be applied with consideration of the individual conditions present in a given field, and how non-nutrient related factors (inadequate irrigation, disease, etc.) can influence tissue nutrient status.

Guidelines for petiole analysis are given only through full bloom growth stage. Beyond that stage the concentration of NO_3-N and PO_4-P can drop to very low levels, even in well fertilized fields; fertilizing to maintain significant petiole NO_3-N and PO_4-P concentrations after full bloom is usually wasteful. After fruit ripening begins even leaf total nutrient concentrations should be interpreted with care. Leaf N, P and K concentration can drop precipitously in the final 4-5 weeks before harvest, particularly in fields with large fruit loads. Fertilization applied after fruit ripening begins will generally not increase yield, and is only useful to keep vines from senescing prematurely.

The sap values contained in Table 7 were calculated by taking the dry petiole standards and adjusting based on the regression equations given in Fig. 11. Great care should be employed when interpreting sap analysis, given the potential confounding factors outlined in this study.

Outreach activities:

Results of this research have been presented at the CDFA-FREP annual meetings in 2007 and 2008. Presentations have also been made at the following tomato grower meetings:

- Bakersfield, Dec. 12, 2007
- Yuba City, Dec. 18, 2007
- Woodland, Jan. 8, 2008
- Modesto, Jan. 31, 2008
- Five Points, Feb. 21, 2008
- Woodland, Jan. 8, 2009
- Modesto, Jan. 29, 2009
- Stockton, Feb. 10, 2009

Additionally, an article on efficient fertigation for processing tomatoes was published in the March, 2008, UCCE 'Vegetable Notes' newsletter sent to hundreds of Central Valley growers and allied industry personnel. Lastly, a comprehensive drip irrigation and fertigation guide was prepared and uploaded to the UC Vegetable Research and Information Center website:
http://vric.ucdavis.edu/pdf/tomato_dripirrigationandfertigation2008.pdf .

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Table 1. Cultural detail and fertilization rates for the UCD and commercial fields monitored.

Year	Field	County	Transplant date	Variety	Texture	Soil characteristics: Olsen P (PPM)	Soil characteristics: Exchangeable K (PPM)	Seasonal fertilizer rate (lb/acre): N	Seasonal fertilizer rate (lb/acre): P_2O_5	Seasonal fertilizer rate (lb/acre): K_2O
2007	UCD	Yolo	9 May	AB2, H9780	loam	11	220			
	Deficient N							80	70	0
	Deficient P							167	0	0
	Adequate N & P							190	70	0
	Excessive N & P							293	140	0
	1	Yolo	4 April	H2601	loam	4	114	169	14	24
	2	Yolo	1 May	AB5	clay loam	16	138	181	14	18
	3	Yolo	10 May	AB2	clay loam	11	110	186	90	33
2008	UCD	Yolo	28 April	AB2, H9780	clay loam	13	284			
	Deficient N							103	70	0
	Deficient P							160	0	0
	Adequate N & P							183	70	0
	Excessive N & P							286	140	0
	4	Fresno	3 April	AB2	clay loam	6	231	166	32	0
	5	Fresno	16 April	H2401	clay loam	6	182	196	67	0
	6	Fresno	19 April	H8004	clay loam	29	439	214	53	0

Table 2. Effect of year, cultivar and fertility treatment on crop biomass and total fruit yield, UC Davis trials

	Dry weight (lb/acre)			Fruit yield	Fruit	Fruit soluble	Biomass nutrient content (lb/acre)		
Year	Vine	Fruit	Total	(tons/acre)	color[z]	solids (^{o}brix)	N	P	K
2007	3,906	6,427	10,333	53.1	31	5.5	206	36	317
2008	5,347	7,093	12,441	61.1	25	5.5	262	38	352
	**	**	**	**	**	ns	**	ns	*
Cultivar									
AB 2	4,850	7,209	12,059	61.4	28	5.5	247	39	365
H 9780	4,403	6,311	10,714	52.8	28	5.5	221	36	304
	ns	**	**	**	ns	ns	*	*	**
Fertility treatment									
Deficient N	4,075 b[y]	5,867 b	9,978 b	47.8 c	27	5.6	175 c	35 b	284 b
Deficient P	4,688 ab	6,626 b	11,470 a	55.3 b	29	5.5	231 b	35 b	328 a
Adequate N and P	4,576 ab	7,130 a	11,769 a	61.9 a	29	5.4	235 b	37 b	355 a
Excessive N and P	5,168 a	7,263 a	12,629 a	63.5 a	28	5.4	295 a	42 a	370 a
					ns	ns			

[ns, *, **] differences not significant, or significant at $p < 0.5$ or 0.1, respectively; no interactions observed among fertility treatment, cultivar and year

[x] Agtron value (ratio of red to green light reflected from blended juice sample); higher value indicates less ripe

[y] mean separation by Duncan's multiple range test, $p < 0.05$

Table 3. Crop productivity, nutrient uptake and nutrient partitioning in the monitored fields.

				lb/acre								
				Vine nutrient content			Fruit nutrient content			Biomass nutrient content		
Year	Field	Biomass dry wt (lb/acre)	Total fruit yield (tons/acre)	N	P	K	N	P	K	N	P	K
2007	1	7,200	45	55	5	14	136	18	140	191	23	159
	2	9,500	51	72	6	17	171	21	177	243	27	194
	3	9,700	59	65	8	18	179	26	210	245	34	227
2008	4	10,300	51	53	9	56	131	26	241	183	35	297
	5	9,400	49	67	8	40	162	23	192	229	30	232
	6	14,400	71	110	10	101	231	35	348	341	46	449
2007	UCD[z]	10,100	58	52	7	53	157	27	267	208	34	319
2008	UCD[z]	13,400	66	88	10	100	175	30	292	262	40	391
Mean		10,500	56	70	8	50	168	26	233	238	34	284

[z] mean of AB 2 and H 9780 varieties, ‘adequate’ nutrient regime

Table 4. General fertigation template for high-yield processing tomato.

		Weekly rate (lb/acre)	
Growth stage	Duration (weeks)	N	K_2O
2 weeks post-transplanting - early fruit set	2-3	10	0
Early fruit set - full bloom	3-4	30-35	25-30
Full bloom - early red fruit	2-3	20-25	0

Table 5. Soil NO_3-N (PPM) distribution across the wetted zone of the excessive N treatment on 7 July, 2008; each value is the mean of 3 replicate samples, each comprised of 4 soil cores.

Soil depth (inches below drip tape)	Horizontal distance from drip tape (inches)		
	0 [z]	6	12
2	20	8	13
6	16	11	7
12	16	16	7

[z] directly beneath drip tape

Table 6. Whole leaf micronutrient concentration ranges in the monitored fields, and current deficiency guidelines.

Growth stage		%			PPM				
		Ca	Mg	S	Zn	Mn	Fe	B	Cu
flowering	min value	1.6	0.8	0.7	23	60	182	58	14
	max value	5.5	2.0	2.6	51	183	791	191	25
	mean	3.2	1.2	1.3	30	86	535	97	20
full bloom	min value	2.0	0.7	0.7	20	56	248	68	11
	max value	5.5	2.5	3.3	50	144	567	210	35
	mean	4.0	1.2	1.4	31	96	386	135	21
Deficiency level [z]									
Jones et al. (1991)		0.8	0.25	0.25	18	30	30	20	3
Wilcox (1993)		1.0	0.3	0.15	10	24	50	15	4

[z] specified for ‘midbloom’ (Jones et al.) or ‘fruiting’ (Wilcox)

Table 7. Suggested tissue macronutrient sufficiency guidelines.

		Sufficiency level		
Sample type	Nutrient	Early flower	Full bloom	First red fruit
whole leaf	% N	4.0	3.5	2.7
	% P	0.32	0.25	0.23
	% K	2.2	1.6	0.8
dry petiole	PPM NO_3-N	8,000	3,000	
	PPM PO_4-P	2,500	2,000	
	% K	4.5	3.0	
petiole sap	PPM NO_3-N	800	350	
	PPM PO_4-P	160	130	
	PPM K	3,500	2,500	

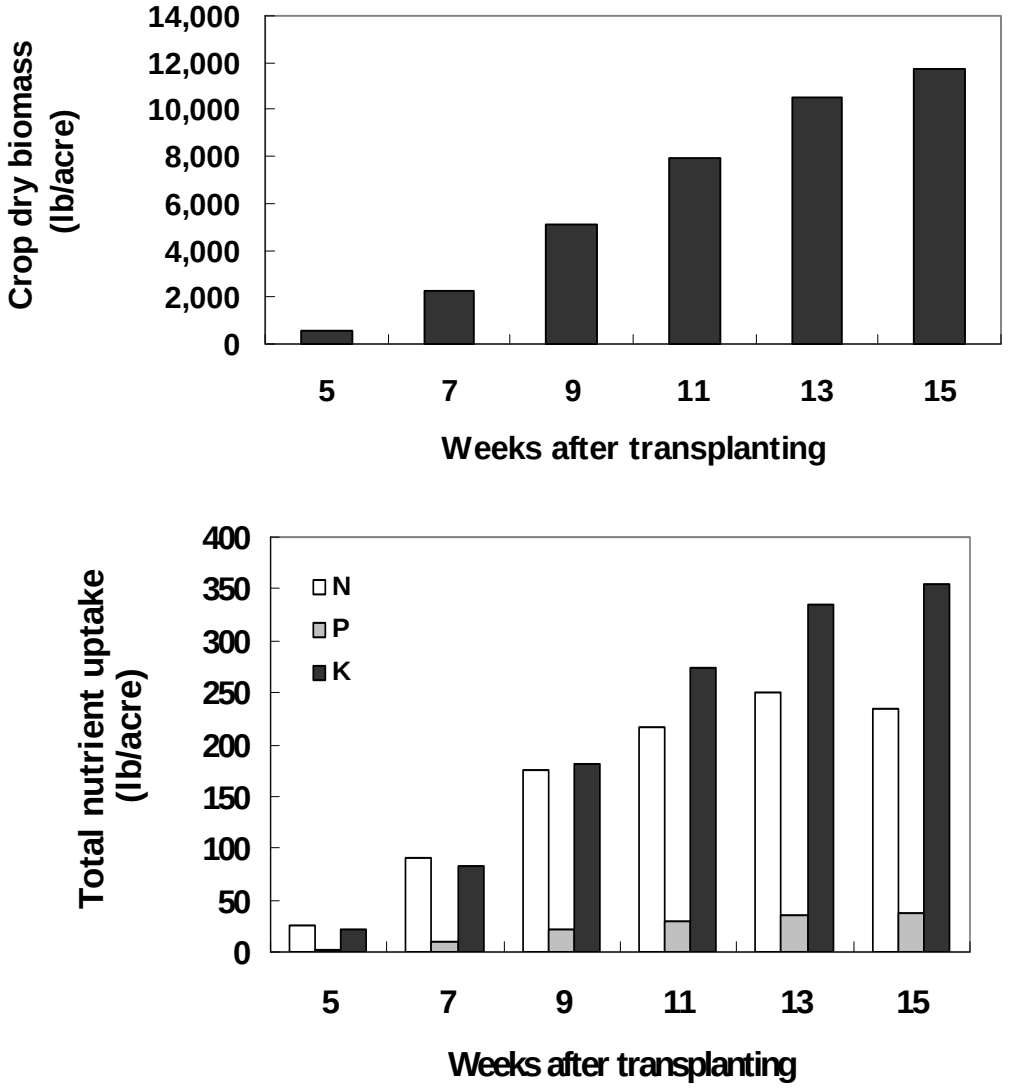


Fig. 1. Pattern of nutrient uptake over the growing season; UCD adequate N treatment, averaged across cultivars and years.

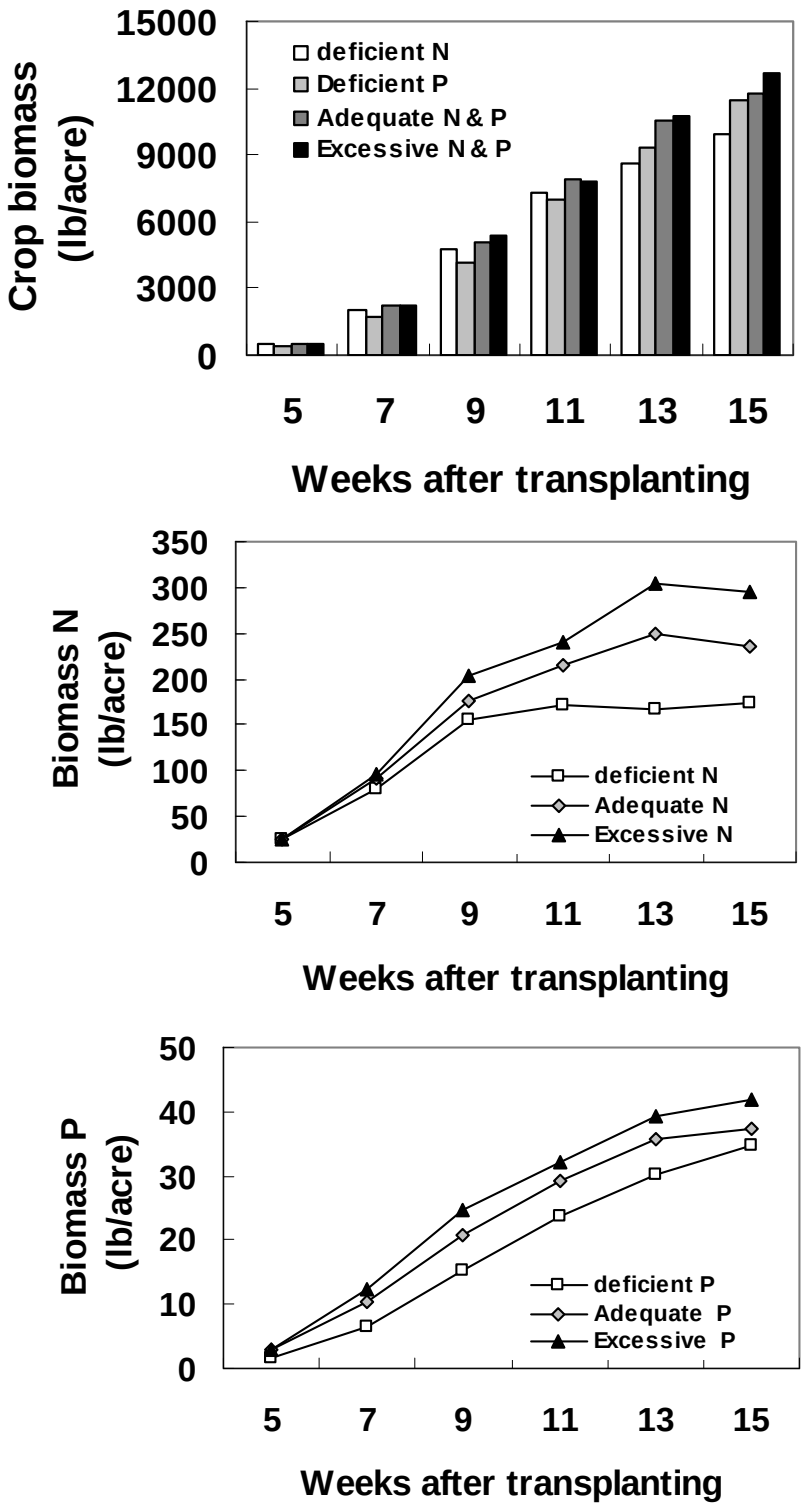


Fig. 2. Effect of fertility treatment on crop biomass development and nutrient uptake at UCD, averaged across cultivars and years.

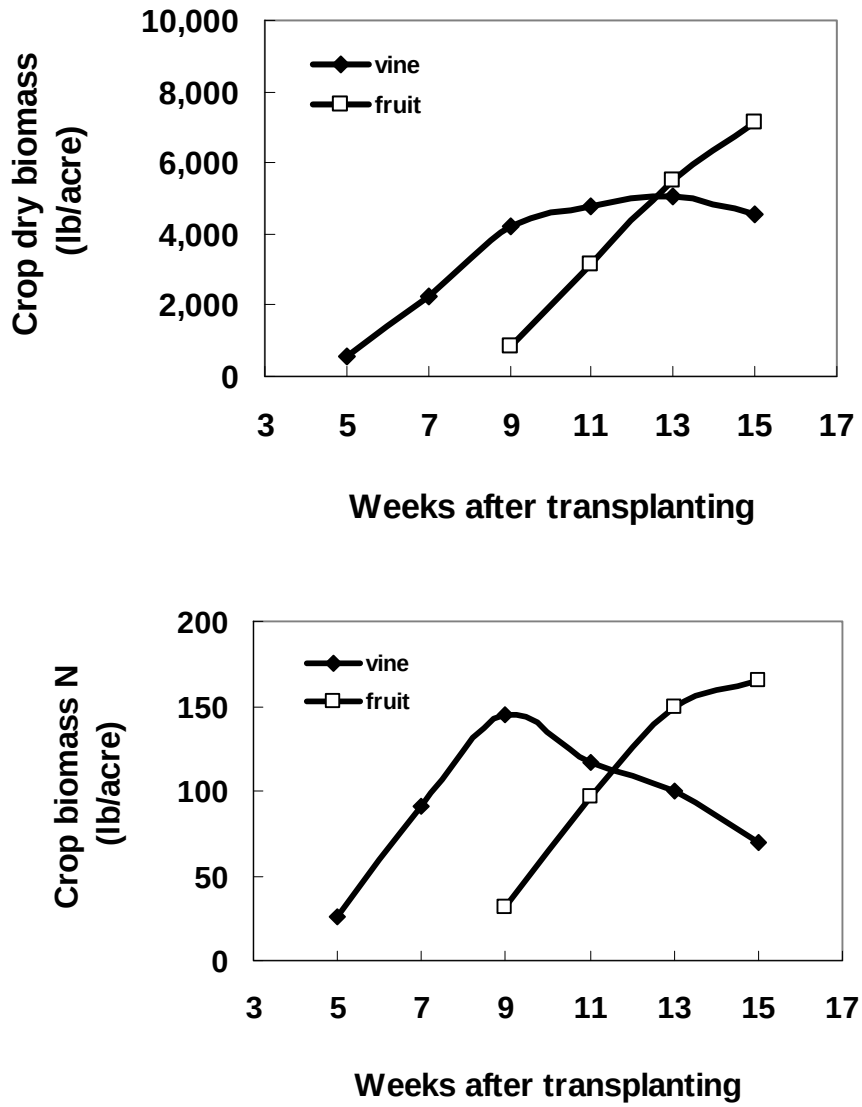


Fig. 3. Partitioning of nutrients between vine and fruit; UCD adequate N treatment, averaged across cultivars and years.

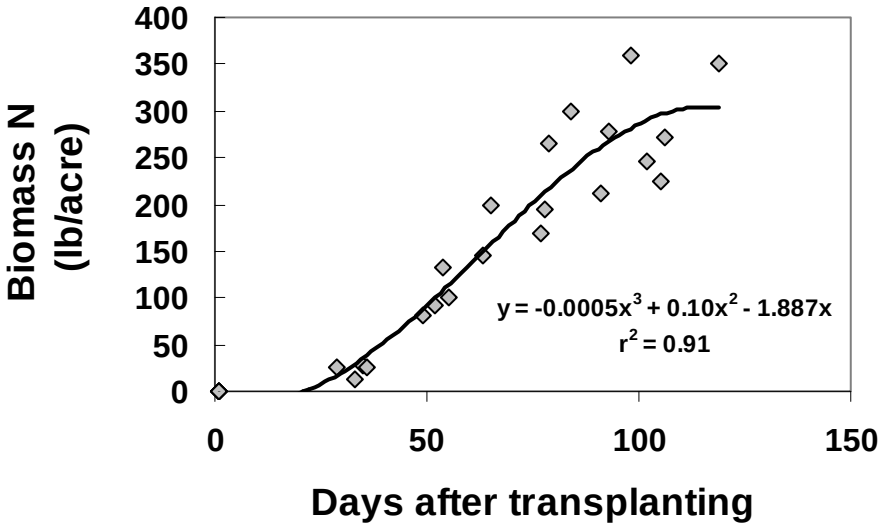


Fig. 4. Biomass N content in the four highest-yielding fields as a function of time after transplanting.

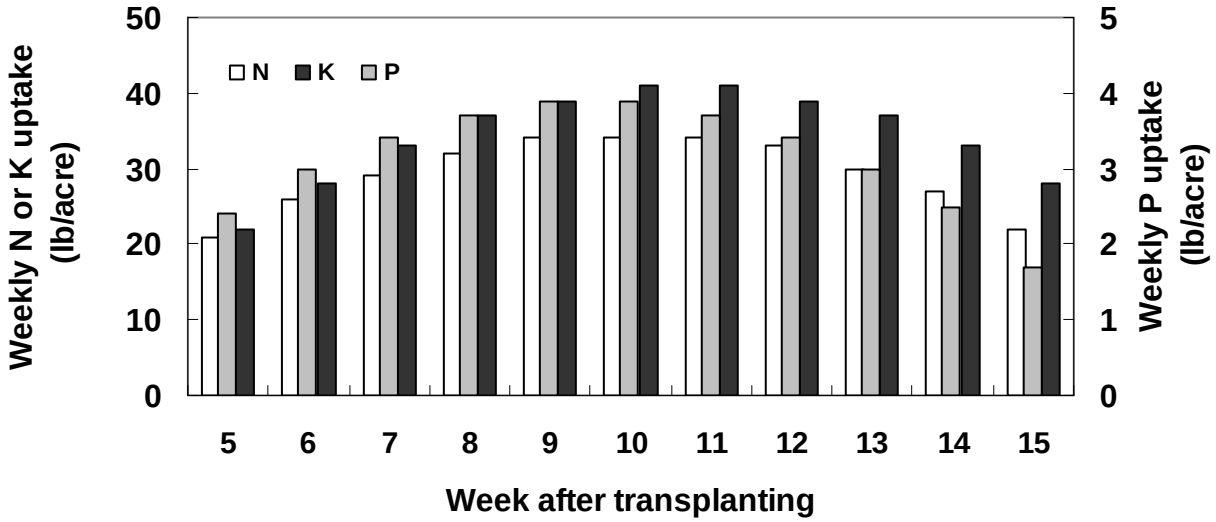


Fig. 5. Weekly crop macronutrient uptake, based on the 4 highest yielding fields.

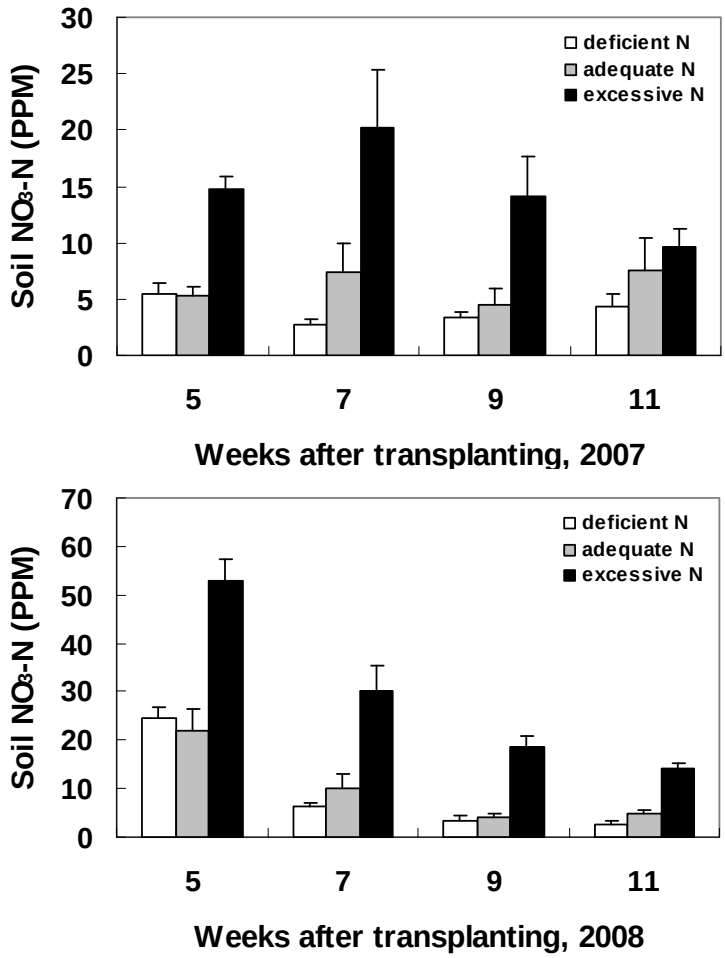


Fig 6. Soil NO_3-N concentration at UCD; sampling of 6-15 inch depth, 4-6 inches from the drip tape; bars indicate standard error of measurement.

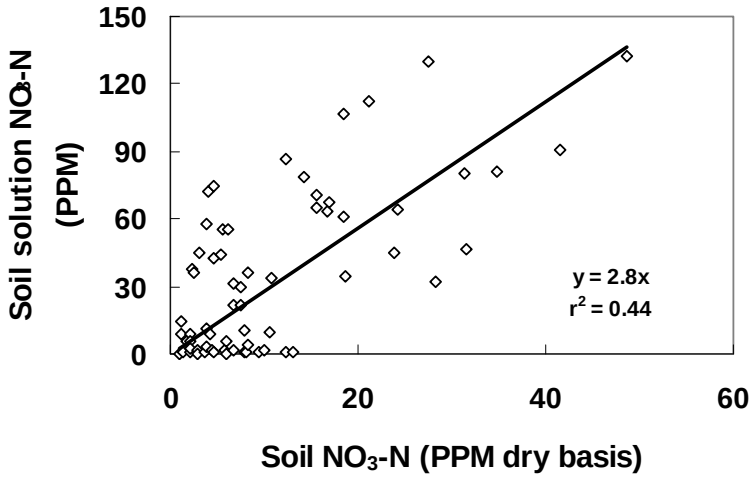


Fig. 7. Relationship between soil NO_3-N and soil solution NO_3-N collected by suction lysimeters, 2007-08 sampling at UCD.

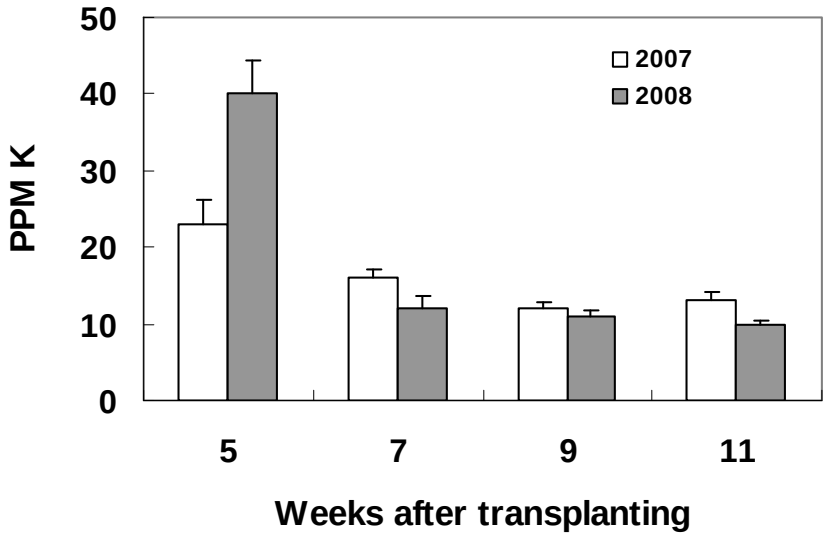


Fig. 8. Soil solution K concentration at UCD, averaged across fertility treatments; bars indicate standard error of measurement.

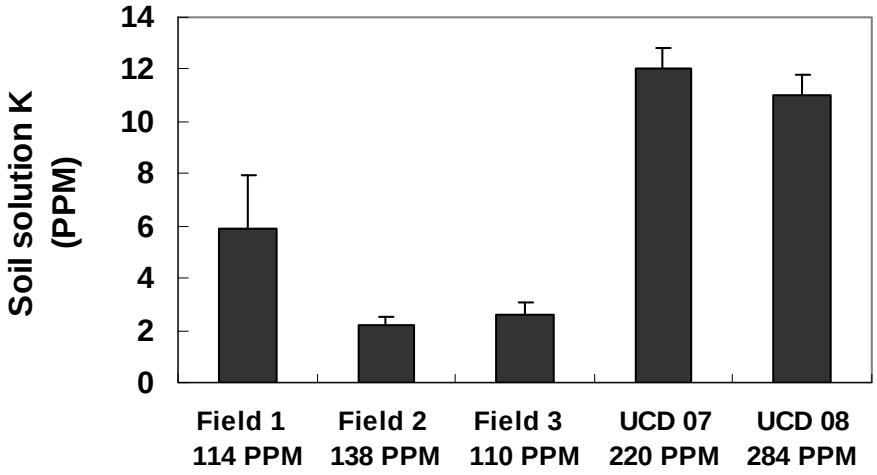


Fig. 9. Soil solution K concentration at full bloom growth stage; soil exchangeable K level give on the x axis. Bars indicate standard error of measurement.

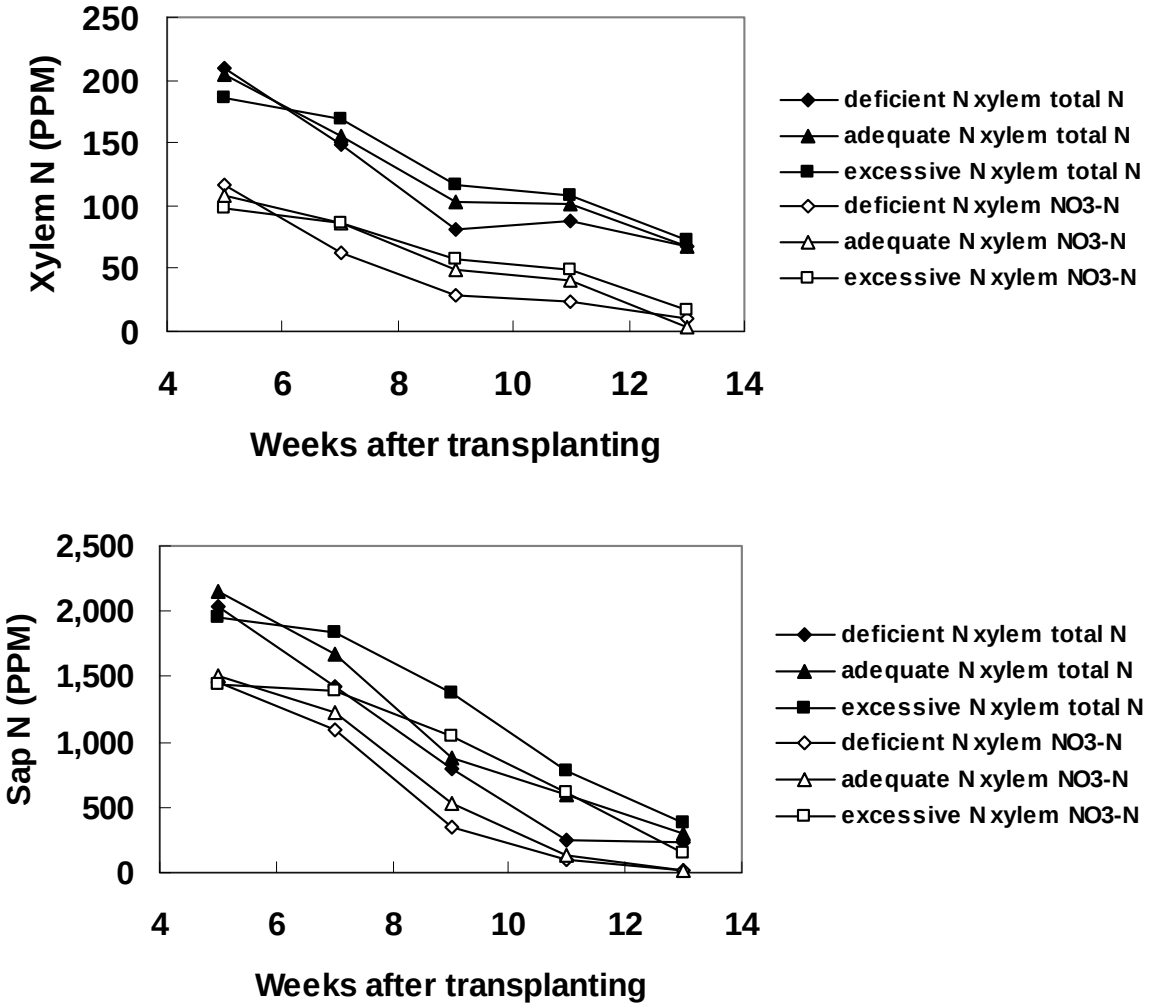


Fig. 10. Nitrogen content and form in xylem solution and fresh petiole sap, 2008 UCD trial; deficient, adequate and excessive refer to N fertigation treatments applied.

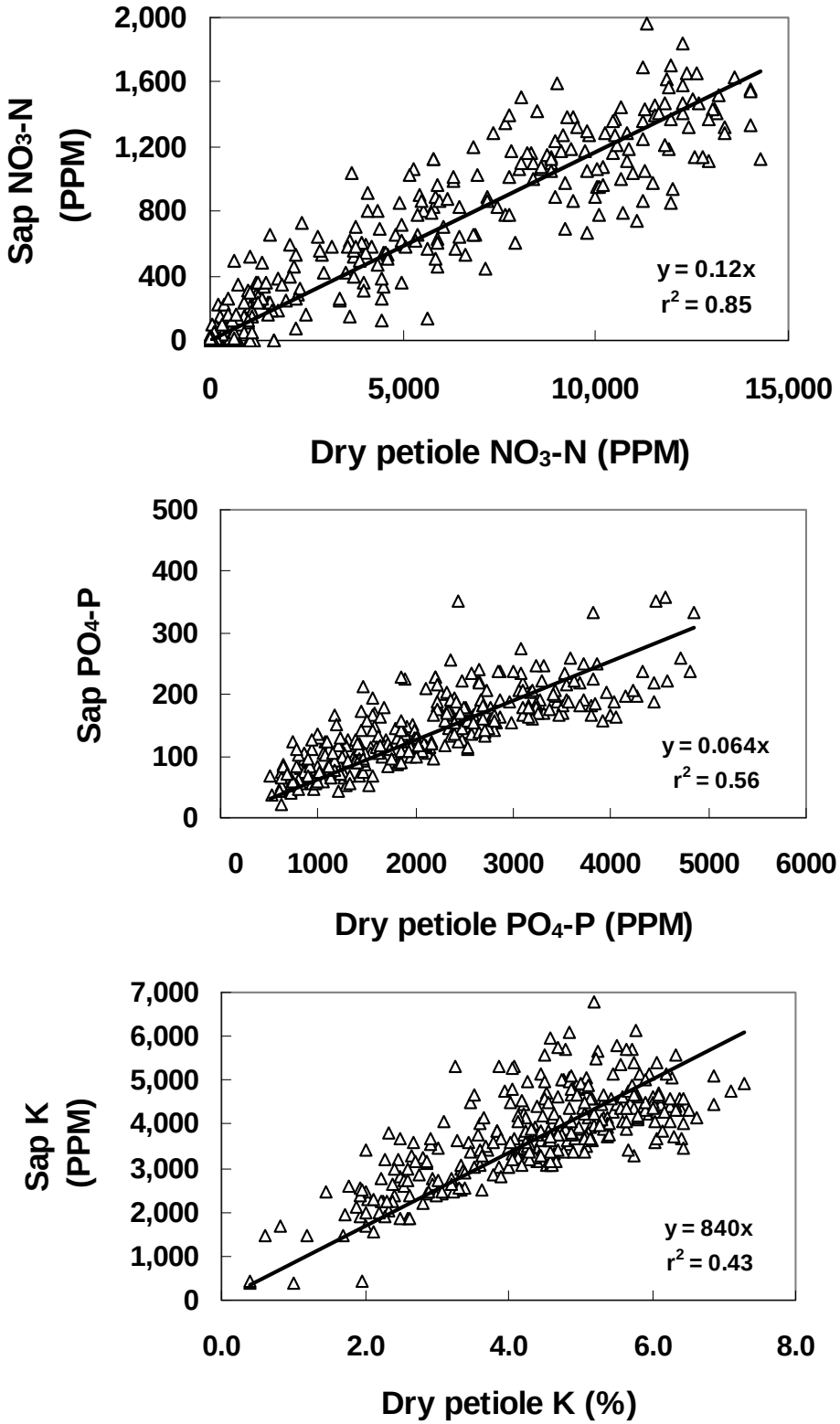


Fig. 11. Relationship between sap and dry petiole NO_3-N, PO_4-P and K concentrations; data from all fields and years combined.

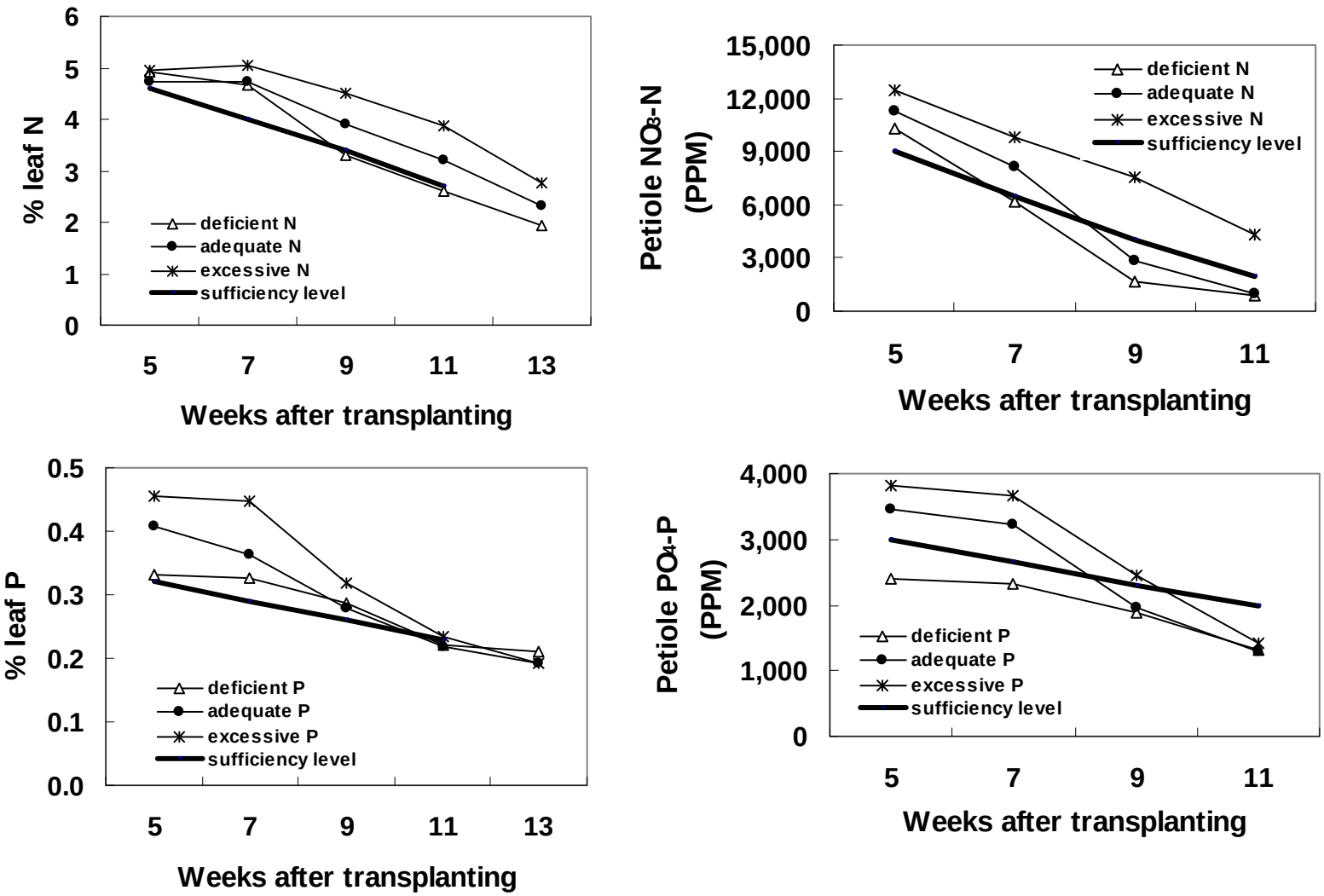
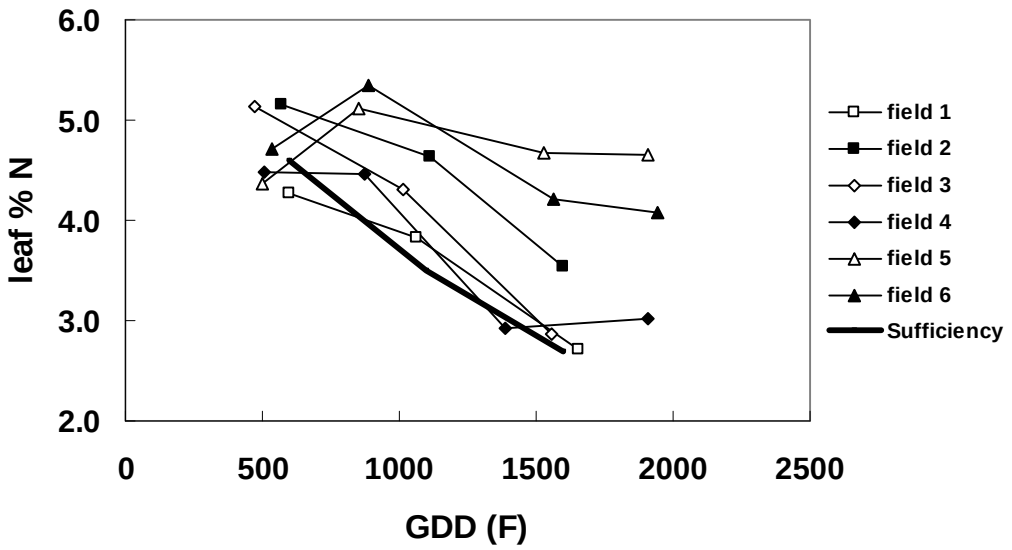


Fig. 12. Tissue N and P status at UCD, averaged across cultivars and years, in comparison with existing sufficiency guidelines.



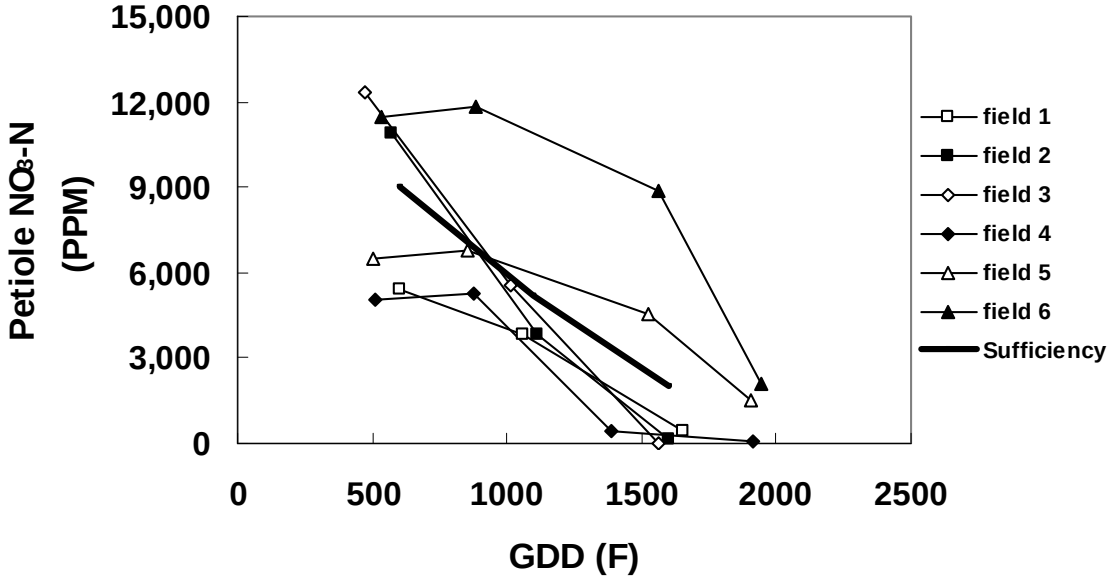


Fig. 13. Tissue N status in the commercial fields in comparison with existing sufficiency guidelines.

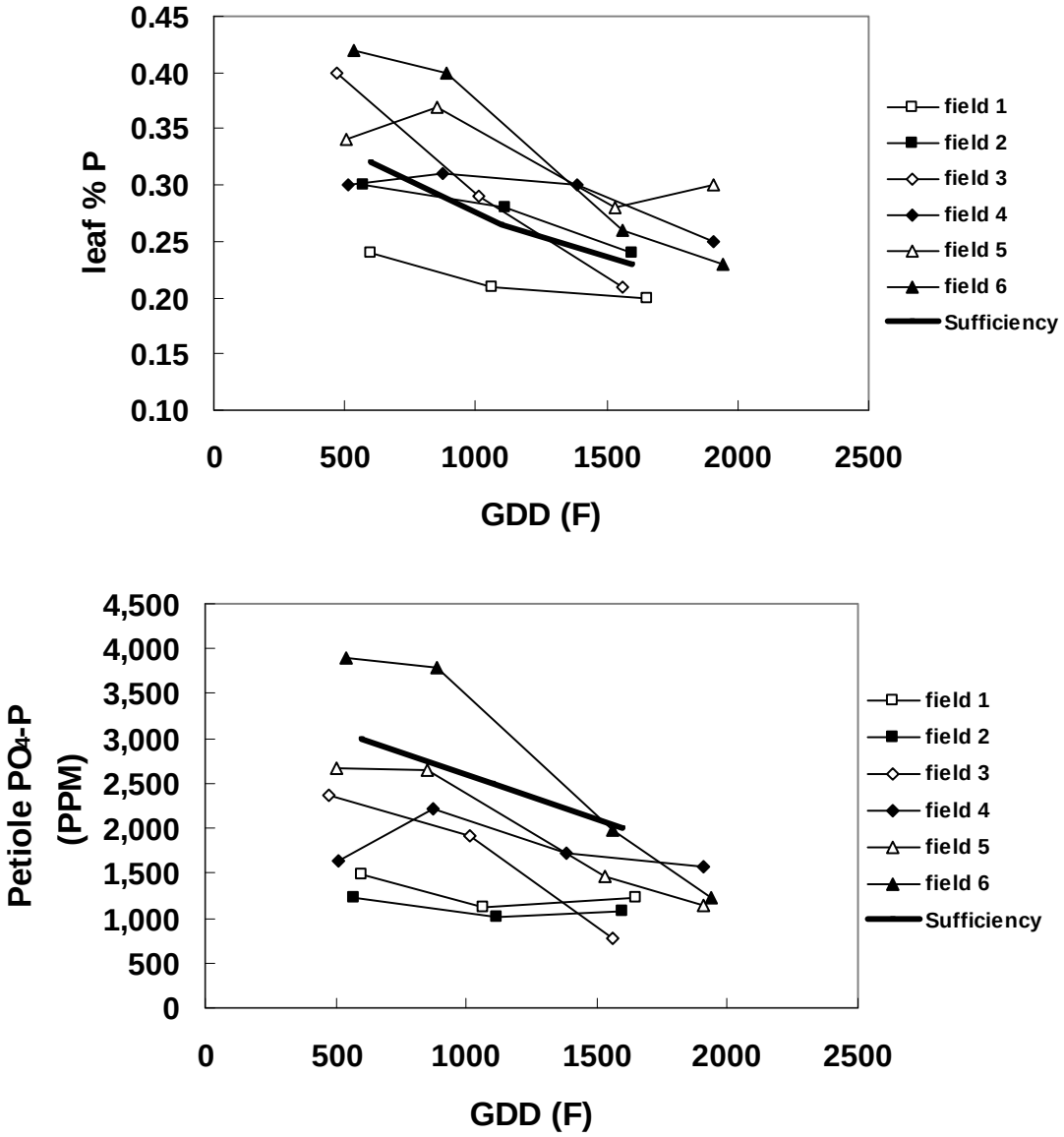
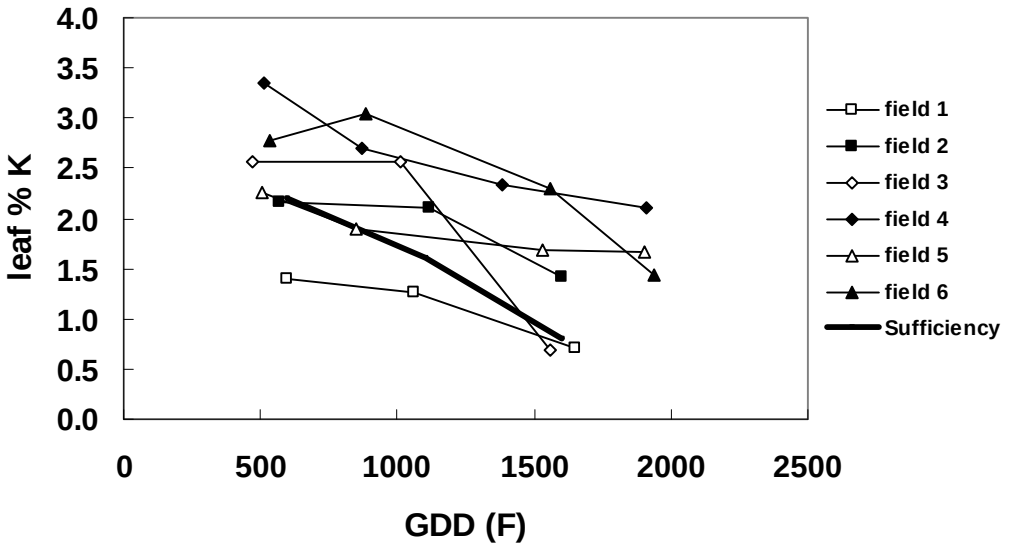


Fig. 14. Tissue P status in the commercial fields in comparison with existing sufficiency guidelines.



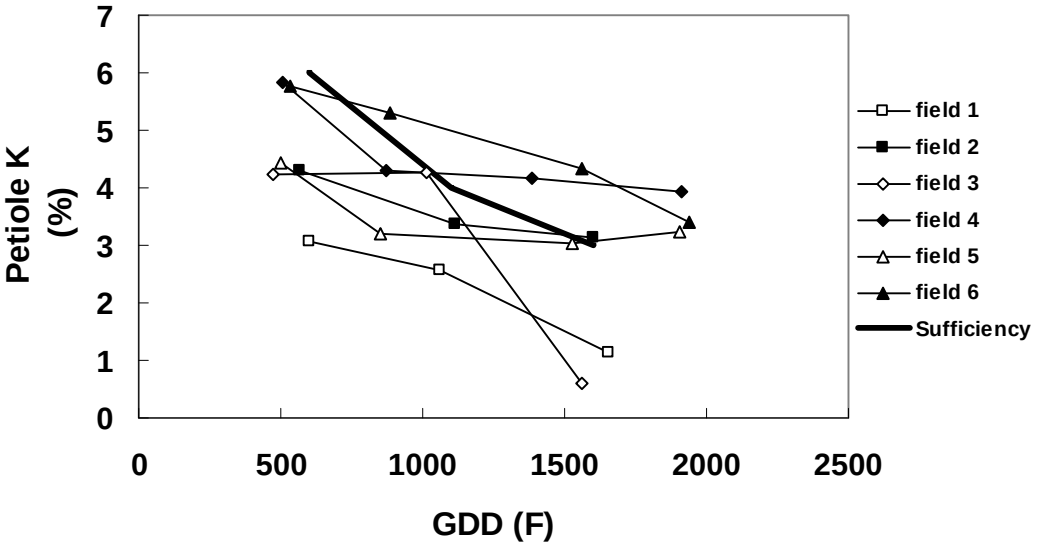


Fig. 15. Tissue K status in the commercial fields in comparison with existing sufficiency guidelines.