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Spatial variation in yield and quality in a small apple orchard

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Abstract We describe the yield and quality of apples from a 0.8 ha apple orchard located in northern Greece over two growing seasons and consider the potential for site-specific management. The orchard has two apple cultivars: Red Chief (main cultivar) and Fuji (pollinator). Yield was measured by weighing all fruit harvested from groups of five adjacent trees and the position of the central tree was recorded by GPS. Apple quality at harvest was evaluated from samples of the two cultivars in both years for which fruit mass, flesh firmness, soluble solids content, juice pH and acidity of the juice were determined. The variation in tree flowering was also measured in the spring of the second season using a stereological sampling procedure. The results showed considerable variability in the number of tree flowers, yield and quality across the orchard for both cultivars. The number of flowers was strongly correlated with the final yield. These data could potentially be used to plan precise thinning and for early prediction of yield; the latter is important for marketing the fruit. Several quality characteristics, including fruit juice soluble solids content and acid content were negatively correlated with yield. The general patterns of spatial variation in several variables suggested that changes in topography and aspect had important effects on apple yield and quality.

Keywords Flowering · Fruit quality · Intrinsic random function-*k* (IRF-*k*) kriging · *Malus domestica* · Precision horticulture · Spatial variation · Stereology

Introduction

Precision agriculture studies have focused largely on arable crops (Yanai et al. 2001; Godwin et al. 2003; Dobermann and Ping 2004; Roel and Plant 2004a). However, high

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value horticultural crops have also been investigated such as citrus (Zaman and Schuman 2006; Ye et al. 2007), olives (López-Granados et al. 2004), apples (Best et al. 2008; Best and Zamora 2008), grapes (Bramley and Hamilton 2003, Taylor 2004; Bramley 2005), cranberries (Pozdnyakova et al. 2005) and tomatoes (Pelletier and Upadhyaya 1999). It is often claimed that precision agriculture can offer a great deal to the production of high value crops, and it is also easier to pay for the investment than for lower value crops. However, detailed analyses of yield, soil, fruit quality properties and their interrelationships should be done before changing traditional management practices to site-specific ones.

Most applications of precision agriculture to date have been in the USA, Canada, Australia and Northern Europe, where fields are large and soil conditions vary considerably (Zhang et al. 2002; Fountas et al. 2004a, b; Griffin et al. 2004). In Greece and southern Europe in general, the application of site-specific management has been slow because of small farm size, a reluctance to adopt new technology, the lack of relevant technology for fruits and vegetables, and the lack of crop subsidies from the European Union (Gemtos et al. 2002). Precision agriculture began to be practiced in Greece in 2001 in cotton production. Yield maps showed significant variation even for small farms (Markinos et al. 2004; Gemtos et al. 2005). However, there has not been any research on precision agriculture of horticultural crops, which are economically the most important crops in Greece.

Apple (*Malus domestica* Borkh.) is the fourth most important tree crop in Greece after olive, citrus and peach (Vasilakakis 2004). Apple quality is determined by how mature the fruit is when harvested. Skin colour, soluble solids content and flesh firmness are the most important maturity indices used for apple harvesting (Blankenship et al. 1997; Marquina et al. 2004). Greek apples are of high quality especially when the orchards are at high elevations, where the fruit develop a good taste and long cold storage potential and red apples develop a deep colour. Red Chief is a clone of Starking Delicious. For Starking Delicious produced under Greek conditions, when soluble solids content is >11.5 g per 100 g of juice, firmness is >63.7 N and with more than 125 chill hours below 12°C, stored apples have good quality with a low susceptibility to superficial scald (personal communication, E. Sfakiotakis, Professor of Pomology, Aristotelian University of Thessaloniki). Malic acid is the main acid in apple juice and it plays an important role in flavour. To our knowledge, optimum values for this property have not been specified as they depend on the variety and stage of maturity.

Fruit quality is generally associated with climate and soil conditions, tree characteristics, and cultural practices. Changes in the latter are the primary means by which orchard managers in Europe have made the transition to intensive production over the past 40 years while meeting market demands for quality and yield. Trees are pruned and trained to have open forms with a central leader and weak open branches. They are managed in this way so that they have relatively low density foliage to avoid shading the lower branches, which reduces yield and quality. Flower- and fruit-thinning are also used to improve fruit size and the annual yield of apple trees. Thinning has become the single most important cultural practice that many growers undertake. Chemical thinning is done on a block basis that does not take into account the variability between individual trees. Hand-thinning is much more costly, but may be necessary if chemical thinning proves inadequate. Many thinning trials have shown that final yields are closely related to flower density, assuming adequate pollination (Lakso and Robinson 1997). Soil conditions become more important in orchards that have a high density of planting, but there is still insufficient knowledge about optimal mineral nutrition of fruit trees (Dris 2002).

Spatio-temporal variation in yield because of alternate bearing of most tree crops, including many apple species, has been the subject of much debate. For example to what extent are fluctuations in yield due to external (exogenous) forces, such as weather and other environmental factors, or to internal (endogenous) forces, such as photosynthesis, internal carbon allocation and energy depletion due to flower and fruit production (Isagi et al. 1997; Hastings 2004; Sakai et al. 2008). Sakai et al. (2008) reconstructed local dynamics from short ecological time series observed in the alternate bearing of 48 satsuma mandarin (*Citrus unshiu* Marc. var. 'Outu Yongou') trees over a seven year period. They showed that yield fluctuation was due to mechanistic (endogenous) forces, and that variation in yield could be predicted without knowledge of the environmental conditions

The aim of this study was to investigate within-field variation in yield, flowering and fruit quality properties of a small apple orchard, and the potential for applying site-specific management.

Materials and methods

Site description

The field studied in 2004 and 2005 is a 0.8 ha commercial apple orchard in the Ptolemaida area of northern Greece (21°50′15″E, 40°39′13″N, mean elevation 790 m). The orchard has a western and a northern aspect and a 6% north–south slope (Fig. 1). The soil texture is a clay. To the north of the orchard there is natural vegetation, to the west is a wheat field, to the east side an apple orchard and to the south a rural road. The orchard was planted in 1998 with two apple cultivars: Red Chief (RC) as the main cultivar and Fuji (FJ) as the pollinator. The orchard has 15 rows, 11 planted with Red Chief and 4 with Fuji (Fig. 1). The between-row spacing is 4 m and the intra-row tree spacing is 2.5 m. Trees were trained as free palmette (Fig. 2).

Sampling

Apples were hand harvested and placed in plastic bins along the tree rows (Fig. 3). All bins from each group of five adjacent trees were collected together and weighed to give an average weight in kilograms of fruit per tree for mapping yield. The geographical position of the middle tree was recorded using a hand-held computer with GPS (Trimble Pathfinder, Pocket 43800) without differential correction (ca. 0.5 m accuracy). In all, 121 yield measurements were obtained for Red Chief and 44 for Fuji.

Before harvest, samples of Red Chief fruit were obtained from 30 georeferenced locations and Fuji fruit from 20 across the orchard. At each location 6 fruit were randomly selected from trees (i.e. 180 RC and 120 FJ fruit in total) and the following quality properties were measured:

1. Fruit mass, by weighing all 6 apples together and calculating the mean value per fruit.
2. Skin colour with a Hunter Lab chromameter (model Miniscan XE plus). The device was calibrated before use with white and black cards. Hue has been found to be a suitable colour measure for several apple varieties (Greer 2005). The hue angle in degrees (H, true red $H = 0°$) was calculated as:

$$H = \tan^{-1}(b/a), \quad (1)$$

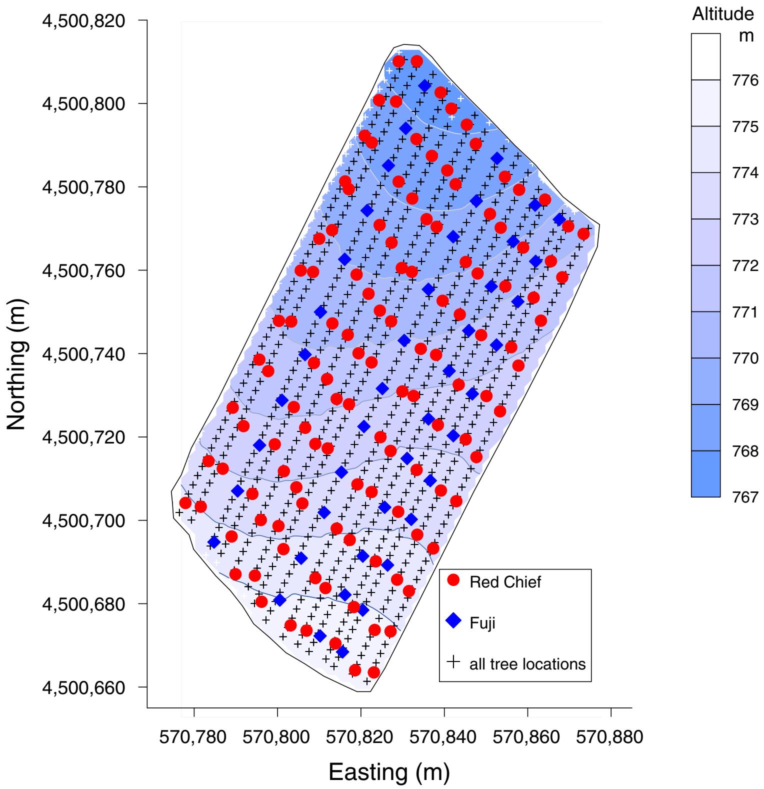

Fig. 1 Orchard layout and topography. Large symbols show georeferenced locations of trees sampled for yield and flower estimation. The north–south slope is 6%

where *a* and *b* are values of L^*a^*b orthogonal colour-space coordinates given by the chromameter (see McGuire 1992). Hue was measured for the Red Chief apples only because their red colour is a quality factor.

3. Flesh firmness (FF) after removal of the skin, using an Effegi penetrometer with 11 mm diameter plunger. The mean of two measurements taken from opposite sides of each sampled fruit was calculated.
4. Soluble solids content (SSC) on juice squeezed from each fruit using a refractometer Carl Zeiss Jena (expressed as g soluble solids per 100 g of juice).
5. Juice pH.
6. Juice acidity by titration with 0.1 N NaOH to an endpoint of pH 8.2 (expressed as g malic acid per 100 g of juice).

Averages of these measurements were calculated for each location. In addition, at each of these 50 locations, the total yield from two adjacent trees was weighed to determine the correlations between quality properties and yield.

In April 2005, estimates were made of the number of flowers per tree using a nested design. From each group of five adjacent trees, one tree was chosen arbitrarily and the number of flowers on the tree was estimated using a systematic uniform random sampling

Fig. 2 Apple trees were trained as a free palmette

Fig. 3 Orchard under study with the harvesting bins placed along the rows. Apples from groups of five adjacent trees were weighed to create yield maps. The north-facing slope can be seen in this view, with shading of trees on the western half of the rows

procedure (Wulfsohn et al. 2006). The palmette shape of the trees in the vertical plane naturally separates each tree in two parts. The number of flower buds was counted on alternate sides of the selected trees (i.e. with probability 0.5). The number of flower buds was then multiplied by 2 (the inverse sampling probability) to obtain an estimate of the total number of buds per tree N_b. Random samples of 20 buds from each variety showed that on average there were 5 flowers per bud. The estimated flower number is then $N_f = 5N_b$. A model-based estimate of the sampling error variance was obtained assuming a Poisson distribution and negligible error for the estimated mean number of flowers per bud:

$$\widehat{\mathrm{var}}(\hat{N}_f) = (10)^2\,\widehat{\mathrm{var}}(\hat{N}_b) = \frac{100}{n}\sum_{i=1}^{n}(1-f)n_{b,i} \approx \frac{100}{n}\sum_{i=1}^{n}0.5n_{b,i}, \quad (2)$$

where n is the number of trees sampled, $n_{b,i}$ is the number of buds in the sample from tree i. The finite population constant, $f = n_{b,i}/N_{b,i}$ where $N_{b,i}$ is the total number of buds on tree i, was estimated as 0.5, i.e. as the sampling probability (Maletti and Wulfsohn 2006). The biological variability of flowering [i.e. the true between-tree coefficient of variance, $\mathrm{CV}(N_f)$] was then estimated by

$$\mathrm{CV}^2(N_f) \approx \mathrm{CV}^2(\hat{N}_f) - \widehat{\mathrm{CE}}^2(\hat{N}_f), \quad (3)$$

where $\mathrm{CV}^2(\hat{N}_f) = \mathrm{var}(\hat{N}_f)/\bar{N}_f$ is the observed (total) coefficient of variance, $\widehat{\mathrm{CE}}(\hat{N}_f) = \sqrt{\widehat{\mathrm{var}}(\hat{N}_f)}/\bar{N}_f$ is the estimated coefficient of error and $\bar{N}_f$ is the estimated mean number of flowers per tree (Wulfsohn et al. 2006).

Yield and quality measurements were made for the two years of the experiment, but the number of flowers was recorded in 2005 only. All sample locations were georeferenced in order to map and explore spatial correlations among properties.

Data analysis

The data analysis was done in two parts. Exploratory data analysis (summary statistics, box plots, Q-Q plots, Kolmogorov–Smirnov test (two sided) for normality, correlation analysis) was carried out using S-PLUS 2000® (MathSoft Inc., Seattle, WA, USA). The Isatis geostatistical software (v. 8.0, Geovariances, Avon, France) was used to determine the spatial relationships of variables. Surfer (v. 8, Golden Software) was used to produce interpolated maps.

Correlation coefficients were computed between the flowering, yield and quality measurements for each season's data. Pearson's product moment coefficient was used, except when at least one of the variables was non-normally distributed at $p < 0.01$ significance level, in which case the Spearman rank correlation coefficient was used. As a result of the alternate bearing of many cultivars of apple, correlations between the number of flowers in 2005 and yields in both 2004 and 2005 were also computed. Aggelopoulou et al. (2007) described the soil data for this site; their analysis of the main crop nutrients showed no correlation with yield or fruit quality properties and these data are not included in this paper.

Data from two seasons is not sufficient to study medium- or long-term temporal variation. Nevertheless, the relative magnitude of spatial (between tree) and temporal (year to year) variation was computed, similar to the approach taken by Roel and Plant (2004b). The coefficient of variation (CV = standard deviation/mean) of a measured variable in a given year provides an estimate of the global spatial variation (each data point is obtained from a different location in the field). The mean spatial variation over the 2 yrs is given by

$$\overline{\mathrm{CV}_S^2}(z) = \frac{1}{2}\left(\mathrm{CV}_1^2(z) + \mathrm{CV}_2^2(z)\right), \quad (4)$$

where $\mathrm{CV}_1^2(z) = \mathrm{var}(z_1)/\bar{z}_1^2$ is the coefficient of variance of variable z for all sampled locations (i.e. trees) in season 1, $\bar{z}_1$ is the mean of z over all locations in season 1, and similarly $\mathrm{CV}_2^2(z) = \mathrm{var}(z_2)/\bar{z}_2^2$ for season 2. The temporal variation for each location was defined as the CV of measurements for a location over time. The mean temporal variation was calculated as the average for all locations, which for two years of data reduces to

$$\overline{\mathrm{CV}_T^2}(z) = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{z_{1,i} - z_{2,i}}{z_{1,i} + z_{2,i}}\right)^2, \tag{5}$$

where n is the number of trees in the sample, $z_{1,i}$ is the measured value of z for tree i in season 1, and $z_{2,i}$ is the measured value of z for tree i in season 2.

The small number of georeferenced locations for quality data was too few for a geostatistical analysis. Variograms were computed and interpolation by kriging was done for Red Chief flowering and yield data only.

Experimental variograms for RC yield and flowering data were computed by Matheron's method of moments (MoM) estimator:

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2m(\mathbf{h})}\sum_{i=1}^{m(\mathbf{h})}[z(\mathbf{x}_i + \mathbf{h}) - z(\mathbf{x}_i)]^2, \tag{6}$$

where $\hat{\gamma}$ is the semivariance, $z(\mathbf{x}_i)$ is the measured value of the variable at location $\mathbf{x}_i$, $\mathbf{h}$ is the lag distance and $m(\mathbf{h})$ is the number of data pairs for lag $\mathbf{h}$. The lag bin sizes were selected to obtain as stable a variogram as possible. Bins of typically 8 or 9 m were used. The variograms were computed to a maximum lag of less than the half the field length. A theoretical variogram model was fitted to each experimental variogram. The minimization was performed using an iterative reweighted least squares procedure with weights proportional to the number of pairs at each lag distance and inversely proportional to the average distance of the lag (Geovariances 2008). Semivariances estimated using fewer than 50 point-pairs were masked in the fitting of variogram models. As part of the exploratory analysis, directional variograms of RC yield and flowering in the along-the-row (SW-NE) and across-the-row (NW-SE) orientations were obtained using a 45° angular tolerance (to obtain sufficient data pairs per bin). Anisotropy was not more thoroughly examined because of the limited number of data.

The exploratory data analysis suggested that there might be trends along and across the field for several variables. In situations where global trend might be expected, as on the slope in our orchard, an alternative method to the MoM variogram estimator is required. The presence of trend indicates a non-stationary process. To some degree non-stationarity is a fuzzy concept because it depends on the scale of the problem (Mandallaz 2000). We used the MoM variogram estimator together with the non-stationary modelling procedure in Isatis to assess whether it was necessary to take account of trend. The non-stationary modelling routine in Isatis is developed within the intrinsic random function of order k (IRF-k) framework in which trend or drift (local trend) is characterized by a linear combination of translation-invariant and pairwise orthogonal basis functions, and generalized covariance functions that filter these basis functions (Delfiner 1976; Cressie 1993; Wackernagel 2003). The non-stationary random variable $z(\mathbf{x})$ at locations $\mathbf{x} = \{\mathbf{x}_1, \ldots, \mathbf{x}_n\}$ is decomposed as

$$z(\mathbf{x}) = m(\mathbf{x}) + \varepsilon(\mathbf{x}) = \sum\nolimits_{j=1}^{n} w_j f_l(\mathbf{x}_j) + \varepsilon(\mathbf{x}), \quad l = 0, 1, \ldots, L, \tag{7}$$

where $m(\mathbf{x})$ is the trend or drift (the expectation or first moment of the random variable), the $L + 1$ basis functions f_l are commonly polynomials of degree less than or equal to k, the weights w_j (where $w_0 = -1$) are unknown coefficients that satisfy

$$\sum\nolimits_{j=0}^{n} w_j f_l(\mathbf{x}_j) = 0, \quad \text{for } l = 0, \ldots, L, \tag{8}$$

and the filtered errors $\varepsilon(\mathbf{x})$ are zero-mean second-order stationary. The number of basis functions depends on the degree k of the trend (see Wackernagel 2003). IRF-k kriging estimates a value at an unsampled location $\mathbf{x}_0$ by minimizing the estimation variance (which is also the variance of residuals):

$$\mathrm{var}\Big(\sum\nolimits_{j=1}^{n} w_j z(\mathbf{x}_j) - z(\mathbf{x}_0)\Big) = \sum_{j=1}^{n}\sum_{k=1}^{n} w_j w_k K(\mathbf{x}_j - \mathbf{x}_k) \tag{9}$$

while respecting the constraint of Eq. 8. The function $K(\mathbf{h}) = \sum\nolimits_{p=0}^{k} b_p K_p(\mathbf{h})$ is a generalized covariance function, b_p are the unknown coefficients to be determined (equivalent to variogram sills) and the $K_p(\mathbf{h})$ are authorized generic structures. In Isatis these may include a nugget, a linear generalized covariance, a spline generalized covariance or a third-order generalized covariance (Geovariances 2008). The IRF-k approach requires data on a regular grid (approximately the case for our orchard data), and Isatis uses a bilinear interpolator to migrate nearby observation locations to the target grid.

The non-stationary analysis was split into two steps. In the first, the degree of polynomial trend to be filtered was determined, and in the second step the corresponding optimal generalized covariance was selected. The trend functions we tested were the Universality condition (i.e. no trend) and combinations of linear and quadratic surfaces in x and y [i.e. 1 x y x^2 xy y^2 where x is the Easting (m) and y is the Northing (m)]. The algorithm uses a cross-validation procedure. The mean experimental error and error variance were estimated for each trend model. Furthermore, each target point was ranked based on the least-squared errors (the first rank was assigned to the polynomial order producing the smallest error) and the ranks were then averaged over the different target points for each model. The latter criterion is less sensitive to outliers than the error variance estimate. The Isatis routine then uses an iterative minimization method following Rao (1971) to estimate generalized covariances compatible with the optimum degree of trend. For the selected orders of the 'best' trend models the proportion of the variance that could be explained by a global trend surface was estimated by ordinary least squares (OLS). The trend surfaces determined using OLS were not used further.

Block kriged estimates were made at the nodes of grids oriented at 27.5° clockwise from North (following the row orientation). For flowering, in which a nested sampling design was used with one or two randomly selected trees out of five adjacent trees in each row, a block size of 4 m × 2.5 m was used. For yield, where measurements were made for five adjacent trees in a row, the block size was 4 m × 10 m. Where there was evidence of significant global trend IRF-k block kriging was used. For visualization purposes, maps of selected Red Chief quality data were created by inverse-squared distance interpolation in Surfer.

Results and discussion

Summary statistics

Univariate statistics for the two cultivars for the two seasons of the experiment are summarized in Table 1, and the spatial and temporal coefficients of variability are given in Table 2. The descriptive statistics indicate considerable variability for the number of

Table 1 Summary statistics of yield, estimated flower numbers and apple quality properties at harvest for two years of sampling

Cultivar	Variable	n	2004					2005				
			Mean	Min	Max	SD_S	Skewness	Mean	Min	Max	SD_S	Skewness
Red Chief	Flowers ($tree^{-1}$)	162[a]	–	–	–	–	–	617	80	1660	51.9	0.75[b]
	Yield (kg $tree^{-1}$)	121	24.9	13.2	36.6	19.3	0.15	24.6	13.8	38.0	22.6	0.10
	Fruit mass (g)	30	196.0	170.0	225.0	7.3	0.15	246.0	202.0	304.0	10.7	0.72†
	Firmness (N)	30	76.8	70.6	82.6	3.9	0.17†	63.9	55.3	75.7	8.6	0.30
	SSC (%)	30	14.9	13.8	16.0	3.8	0.21	15.2	14.0	16.5	4.4	0.26
	Juice pH	30	3.8	3.5	4.2	4.0	0.13	3.8	3.7	4.0	2.1	0.52
	Malic acid (‰)	30	2.96	2.41	3.48	9.1	0.21	3.22	2.68	3.89	12.5	1.14‡
	Hue angle (°)	30	19.1	16.1	32.6	8.3	3.52†	21.6	15.8	31.4	17.4	0.64
Fuji	Flowers ($tree^{-1}$)	44[a]	–	–	–	–	–	458	80	1940	82.9	1.97[b]
	Yield (kg $tree^{-1}$)	44	51.2	27.1	70.4	16.7	0.38	25.3	12.0	50.0	40.9	1.00‡
	Fruit mass (g)	20	235.0	203.0	267.0	7.4	0.34	253.0	226.0	296.0	6.9	1.17[c]
	Firmness (N)	20	71.9	67.2	78.5	3.6	0.89	74.8	70.2	78.3	2.6	0.52
	SSC (%)	20	15.7	15.0	16.6	2.9	0.40	16.8	15.8	17.7	3.3	0.50
	Juice pH	20	3.3	3.1	3.5	3.6	0.42	3.5	3.4	3.6	2.0	0.08
	Malic acid (‰)	20	3.82	3.48	4.49	6.3	1.12[c]	5.02	3.89	5.90	11.2	0.89[c]

$SD_S = \sqrt{\mathrm{var}(Z)}$ is the standard deviation for a given year based on measurements at all spatial locations

Kolmogiriv–Smirnov test ($n \geq 30$) indicates cdf is not the normal at † $p < 0.05$, ‡ $p < 0.01$ significance

[a] 2005 only

[b] Kolmogiriv–Smirnov test ($n > 30$) indicates cdf is not the normal at $p < 0.01$ and cdf of logarithmically transformed variable is normal with $p > 0.05$

[c] Distribution judged significantly different from the normal from Q–Q plots ($n < 30$). Cases where distribution appears close to normal when 1–2 outliers are not included

Table 2 Spatial and temporal variability of fruit yield and quality

Cultivar	Variable	$\overline{CV}_S$ (%)	$\overline{CV}_T$ (%)	$R_{S/T}$
Red Chief	Yield (kg tree^{-1})	21.0	9.9	4.5
	Fruit mass (g)	9.2	11.1	0.7
	Firmness (N)	6.7	9.3	0.5
	SSC (%)	4.1	2.2	3.5
	Juice pH	3.2[a]	2.1[a]	2.3
	Malic acid (‰)	10.9	6.7	2.6
	Hue angle (°)	13.6[a]	47.1[a]	0.1
Fuji	Yield (kg tree^{-1})	31.2	36.5	0.7
	Fruit mass (g)	7.2	4.9	2.2
	Firmness (N)	3.1	2.8	1.2
	SSC (%)	3.1	3.5	0.8
	Juice pH	2.9[a]	3.3[a]	0.8
	Malic acid (‰)	9.1	13.2	0.5

$\overline{CV}_S$ is the mean spatial coefficient of variation $CV_S = SD_S(Z)/\bar{Z}$ over the two years where SD_S is the standard deviation for a given year based on measurements at all spatial locations. $\overline{CV}_T$ is the mean temporal CV averaged over all tree locations. $R_{S/T}$ is the ratio $\overline{CV}_S^2/\overline{CV}_T^2$

[a] These values are only indicative due to the lack of a true zero for the variables

flowers, moderate variation for yield and little variation in the quality properties. The number of flowers per tree is very variable with CV_S values of 51.9% and 82.9% for RC and FJ, respectively. The mean sample size per tree is 62 buds for RC and 46 for FJ. The estimated coefficient of error $CE(\hat{N}_f)$ is 10.4% for RC and 13.6% for FJ. Using Eq. (3), $CV_S^2(N_f) = 0.519^2 - 0.104^2 = 0.508^2$ for RC and $CV_S^2(N_f) = 0.818^2$ for FJ. Over 95% of the total variance, $CV_S^2(\hat{N}_f)$, for both RC and FJ is biological variability, indicating that the bud sampling scheme was sufficiently precise. The coefficient of variation (CV_S) for yield is 16–24% for the two cultivars and the two years except for Fuji in 2005 when the CV_S of yield is about 40%. In 2004 Fuji had approximately double the yield of that in 2005. Fuji is a strongly alternate bearing cultivar (alternating high and low yields from year to year).

Table 2 indicates that the temporal variation in yield over the two years is much greater for FJ ($\overline{CV}_T = 36.5\%$) than for RC ($\overline{CV}_T = 9.9\%$). This is due to the strong alternate bearing of Fuji. For the quality properties the temporal variation was rather small ($\overline{CV}_T$: 2.1–13.2%), except for RC hue.

Large numbers of fruits per tree were associated with reduced quality in the 2005 season. There is a statistically highly significant decrease in soluble solid content for Red Chief apples on trees with more flowers (Table 3), but the association is not evident for yield. For Fuji flesh firmness, soluble solid content and malic acid content decrease, and pH increases with yield (Table 4).

For Red Chief (Table 3), as fruit mass increases, flesh firmness decreases because of fruit maturity. Greer (2005) found that hue angle provided a consistent quantity for discriminating between ripening patterns in two apple varieties ('Royal Gala' and 'Braeburn'). In this study there is a significant negative correlation between colour expressed as hue angle and flesh firmness (also a measure of maturity) for Red Chief in 2005 (decreasing hue implies more red in the colour), but not in 2004 when there was little variation in hue.

Correlations between the estimated number of flowers and yield for both years are given in Table 5. The correlations between flowering and yield in 2005 are strong for Fuji

Table 3 Correlations between flowering, yield and quality at harvest for Red Chief apples ($n = 30$)

2004	2005						
	Yield	Fruit mass	FF	SSC	pH	Malic acid	Hue angle
ln(flowers tree^{-1})		−0.16	0.37*	−0.66**	0.23	−0.08[a]	−0.28
Yield (kg tree^{-1})		0.02	0.05	−0.33	0.04	0.03[a]	−0.09
Fruit mass (g)	0.30		−0.50**	0.12	0.26	0.03[a]	0.37*
FF (N)	−0.28	−0.78**		−0.28	0.10	−0.03[a]	−0.69**
SSC (%)	−0.22	−0.04	0.25		−0.06	0.16[a]	0.18
Juice pH	0.04	0.05	0.01	0.26		−0.38*[,a]	−0.07
Malic acid (‰)	−0.17	−0.21	0.32	0.08	−0.22		0.12[a]
Hue angle (°)	0.06[a]	0.00[a]	−0.07[a]	−0.39*[,a]	−0.36*[,a]	0.14[a]	

Correlation coefficients are for within-year data only. Values in the lower triangle of the matrix are for 2004, values in the upper triangle for 2005. Correlations between yield and flowering in 2005 are reported in Table 5

* Under independence of measurements, significant at $p < 0.05$

** Under independence of measurements, significant at $p < 0.01$

[a] Spearman rank correlation coefficient

Table 4 Correlations between flowering, yield and quality at harvest for Fuji apples ($n = 20$)

2004	2005					
	Yield (kg tree^{-1})	Fruit mass (g)	FF (N)	SSC (%)	pH	Malic acid (‰)
ln(flowers tree^{-1})		−0.10	−0.69**	−0.60**	0.12	−0.79**
Yield (kg tree^{-1})		−0.21[a]	−0.63**[,a]	−0.46*[,a]	0.44*[,a]	−0.45*[,a]
Fruit mass (g)	−0.26		−0.01	0.10	−0.30	0.13
Flesh firmness (N)	−0.18	0.10		0.44	−0.30	0.72**
SSC (%)	−0.72**	−0.07	0.43		−0.37	0.61**
Juice pH	0.01	0.16	−0.30	−0.37		−0.29
Malic acid (‰)	−0.20	−0.16	0.29	0.61**	−0.32	

Correlation coefficients are for within-year data only. Values in the lower triangle of the matrix are for 2004, values in the upper triangle for 2005. Correlations between yield and flowering in 2005 are reported in Table 5

* Under independence of measurements, significant at $p < 0.05$

** Under independence of measurements, significant at $p < 0.01$

[a] Spearman rank correlation coefficient

($r = 0.82$) and moderate for Red Chief ($r_S = 0.60$). The number of flowers per tree provides an upper limit on fruit number, which is then adjusted depending on fruit thinning practices. An estimate of the number of flowers early in the season can be useful for both the farmer and the industry to predict yield, reduce production costs by varying fertilizer application and for market planning. Lack of correlation between fruit mass and tree yield indicates that increases in yield are related to the number of fruit rather than to fruit size. Plots of tree yield against the estimated number of fruit per tree (yield divided by fruit mass) for RC 2005 illustrate this (Fig. 4a). Flower and bud numbers are plotted against fruit number in Fig. 4b. The lack of relationship between yield per tree and fruit size is probably due to fruit thinning.

Table 5 Correlations between tree yield (kg of fruit) in 2004 and 2005 and log-transformed flowers in 2005

Fuji	Red Chief		
	2004 yield	2005 yield	2005 ln(flowers)
2004 yield (kg $tree^{-1}$)		0.33**	−0.10
2005 yield (kg $tree^{-1}$)	0.15		0.60**[,a]
2005 ln(flowers $tree^{-1}$)	0.08	0.82**	

Pearson product-moment correlations are for within-cultivar only. Values in the lower triangle of the matrix are for Fuji ($n = 44$), values in the upper triangle for Red Chief ($n = 121$)

** Under independence of measurements, significant at $p < 0.01$

[a] Spearman rank correlation coefficient

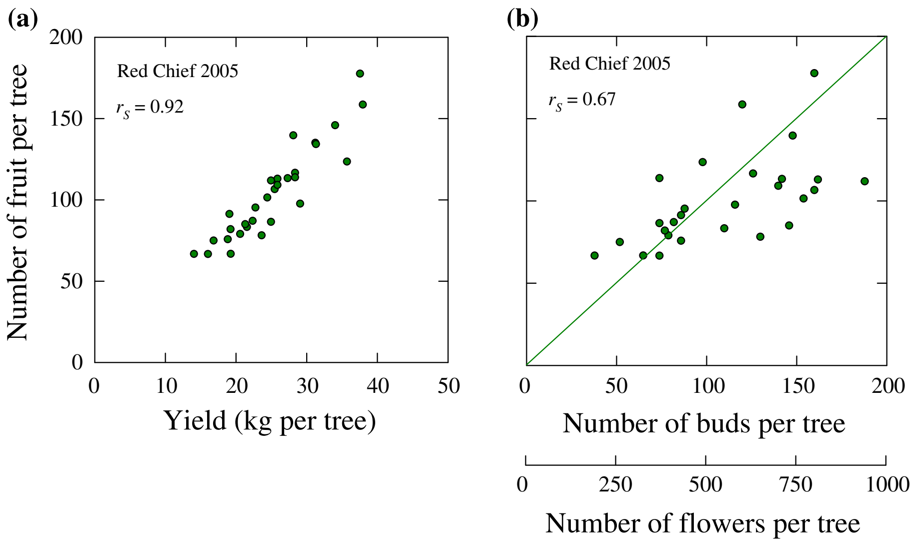

Fig. 4 Estimated numbers of fruit per tree versus: **a** yield in kg per tree and **b** flowering buds per tree for Red Chief in 2005 (the diagonal is the identity line for buds and fruit). Fruit number per tree was derived from measured yield (kg) and fruit mass

Spatial analysis

The non-stationary modelling of trend indicates that several properties are non-stationary (Table 6) and this is supported by the pattern of variation in the interpolated maps (Figs. 6 and 7). The spatial variation of most Red Chief properties show a NW-SE trend over the field and to a lesser extent along the SW-NE oriented rows. This is probably due to the western and northern aspect of the field, and thereby patterns of light availability. The criteria for selecting the preferred trend model are a smaller mean rank and error variance. Table 6 shows that the model selected can depend on the criterion.

Selected variograms and maps for Red Chief, the main cultivar, are shown in Figs. 5, 6, and 7. Fitted variogram or generalized covariance model parameters are summarized in Table 7. Figure 5a shows the directional (45° angular tolerance) experimental variogram for 2004 yield. The solid line shows the model fitted to the omnidirectional variogram

Table 6 Summary of trend modelling trials for Red Chief data

Property	Year	Trend trial	Mean rank	Mean of error	Variance of error	%Variance[a]
Flowers per tree	2005	No trend	1.2	0	104 060	
		$1\ x\ y\ x^2\ xy\ y^2$	0.8	−0.1411	69 535	44.1
ln(flowers per tree)	2005	No trend	2.1	0	0.0299	
		$1\ x\ y\ x^2\ xy\ y^2$	1.8	−0.000219	0.0209	35.6
Yield per tree (kg)	2004	No trend	1.2	0	23.5	
		$1\ x\ y$	1.1	0.0171	20.2	17.7
		$1\ x\ y\ x^2\ xy\ y^2$	0.75	0.00107	15.7	39.4
	2005	No trend	1.3	0	31.1	
		$1\ x\ y\ x^2\ xy\ y^2$	0.74	0.00301	25.5	24.6
Flesh firmness (N)	2004	No trend	1.8	0	9.4	
		$1\ x\ y\ x^2\ xy\ y^2$	1.1	−0.0119	7.9	43.5
	2005	No trend	2.1	0	30.6	
		$1\ x\ y$	0.57	−0.021	15.2	57.0
Fruit mass (g)	2004	No trend	1.5	0	201.9	
		$1\ x\ y$	1.2	−0.217	213.6	18.8
	2005	No trend	1.6	0	718.3	
		$1\ x\ y$	1.3	−0.407	604.1	29.7
SSC (%)	2004	No trend	1.1	0	0.334	
		$1\ x\ y$	1.5	−0.0057	0.378	0.4
	2005	No trend	1.5	0	0.464	
		$1\ x\ y$	1.5	0.00893	0.389	29.7
Malic acid (%)	2004	No trend	1.5	0	0.000741	
		$1\ x\ y\ x^2\ xy\ y^2$	1.2	0.000679	0.000640	37.9
	2005	No trend	1.4	0	0.00173	
		$1\ x\ y\ x^2\ xy\ y^2$	1.5	0.000774	0.00150	42.1

Results are given for no-trend and for the best fitting polynomial models

[a] Estimate of proportion of total variance accounted for by trend model determined using ordinary least squares

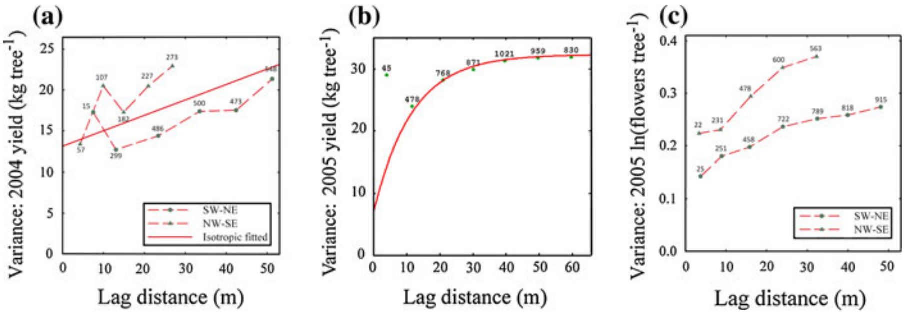

Fig. 5 Variograms of **a** 2004 yield (kg tree^{-1}), **b** 2005 yield (fitted omni-directional) and **c** 2005 flowers tree^{-1} for the Red Chief cultivar. The directional variogram in (**a**) and (**c**) was computed with 45° angular tolerance in along-the-row (SW-NE) and across-the-row (NW-SE) directions. The *solid line* in (**a**) is the fitted omnidirectional variogram model. The labels show the number of paired comparisons

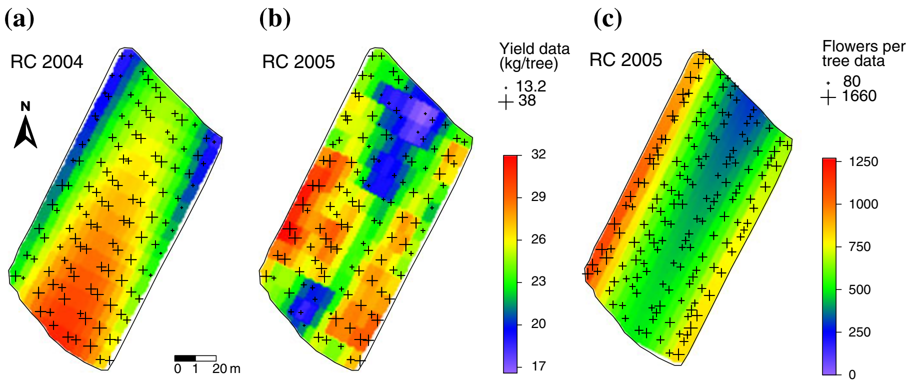

Fig. 6 Maps of **a** 2004 yield (kg tree^{-1}), **b** 2005 yield (kg tree^{-1}) and **c** flowers (tree^{-1}) for the Red Chief cultivar. The scale bar represents interpolated values; the symbols indicate measured data values

(nugget variance of 13.1 and gradient of 0.189). The patterns of increasing variance with lag distance indicate trends along and across the orchard. The smallest mean rank and error variance are for the quadratic trend surface, which accounts for about 39.4% of the observed variance compared to 17.7% for a linear surface (Table 6). We used IRF-*k* with a quadratic trend for block kriging the 2004 yield data. The covariance of the residuals was pure nugget (Table 7). Marcotte and David (1988) showed that IRF-*k* kriging when the covariance of residuals is nugget is equivalent to universal kriging, except that universal kriging reinstates the measured values at the observation points (it is an exact interpolator). The kriged map is shown in Fig. 6a. In the case of yield 2005, in both the NW-SE and SW-NE directions the variance increases with lag distance. For lag distances greater than 30 m (half the NW-SE dimension of the orchard) the SW-NE (along-the-row orientation) variogram becomes bounded so that an exponential omnidirectional theoretical variogram provides an acceptable model for the spatial relations (Fig. 5b and Table 7). The omni-directional variogram has an effective range (approaching 95% of the sill) of 35 m. The map shown in Fig. 6b was produced by ordinary block kriging (4 m × 10 m block).

The distribution of flowers per tree is positively skewed and a Kolmogiriv–Smirnov test indicates that the data could be represented by a lognormal distribution (Table 1). The directional experimental variogram for ln-transformed flower data is shown in Fig. 5. The directional variogram indicates trend along both the SW-NE and NW-SE directions. A quadratic trend surface accounted for 44.1% of the variance of flower data and 35.6% of the variance of log-transformed flower data. IRF-*k* block kriging (4 m × 2.5 m block) of flowering data highlights the SW-NE trend and edge patterns (Fig. 6c). For 2005 both flower numbers early in the season and the final yield are higher along the outer edge rows.

Figure 7 also illustrates typical patterns of variation across the orchard and the considerable variation between the two growing seasons using two of the quality variables as examples. The RC 2004 malic acid content has distinctly different values in the northern and southern parts of the orchard (Fig. 7c). Figure 7b shows a NW-SE trend across the site for 2005 flesh firmness. Flesh firmness in 2005 has 57% of the variance accounted for by a linear trend (Table 6). Reflecting the negative association with flesh firmness (Table 3), fruit mass data from 2005 have distinctly higher values on the east side of the orchard where flesh firmness is low (Fig. 7b). A linear trend surface explains almost 30% of the variation in fruit mass for 2005 (Table 6).

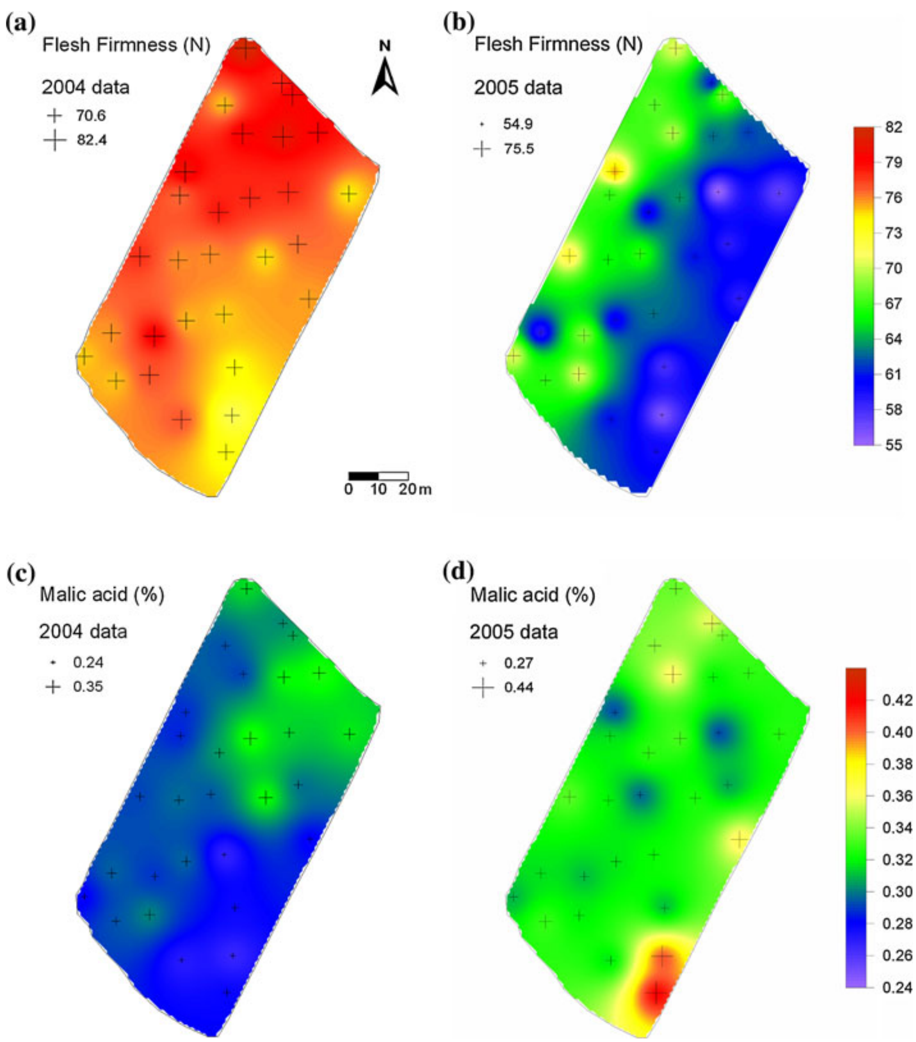

Fig. 7 Maps of **a** flesh firmness 2004, **b** flesh firmness 2005, **c** malic acid content 2004 and **d** malic acid content 2005 for the Red Chief cultivar. Interpolation was done by inverse-squared distance. The scale bar represents interpolated values; the symbols indicate measured data values

Implications for site-specific management

The spatio-temporal patterns of quality and yield variation over the field have implications for management. These are preliminary assessments because only two seasons of data were obtained. Sakai et al. (2008) showed that at least four years of data were needed to understand patterns of alternate bearing in a citrus orchard.

The yield map for 2004 (Fig. 6a) shows that the southern part of the orchard was higher yielding than the northern part. Trees were also generally larger in the southern part of the orchard. The greater number of flowers and larger yield in 2005 occur along edges of the field, Fig. 6b, c. Slope aspect and light availability are likely to be key factors in partly explaining this variation in yield and quality.

Table 7 Parameters of variogram models or generalized covariance functions used for kriging Red Chief yield and flower data

Property	Year	Order of trend	Procedure[b]	Model type	Nugget	Sill of the spatially dependent component	Effective range (m)
Yield (kg $tree^{-1}$)	2004	2	IRF-*k*/GC	Nugget	14.75	–	–
Yield (kg $tree^{-1}$)	2005	0	OK/MoM	Exponential	7.0	25.0	35.0
ln(flowers $tree^{-1}$)	2005[a]	2	IRF-*k*/GC	Nugget	0.201	–	–

[a] Property identified as non-normally distributed (Table 1)

[b] OK = ordinary block kriging; MoM = method of moments variogram, IRF-*k* = intrinsic random function of order *k* block kriging; GC = generalized covariance of residuals

The yield maps show alternate bearing in parts of the orchard, i.e. areas where if yield was large in 2004, then it was low in 2005 and vice versa. In the northern part of the orchard yield was low in both years. More years of data would be required to detect whether this is an indication of lower yield potential in this part of the orchard, or a result of the yield dynamics. The soil is visibly rockier in the northern, lower lying part of this orchard. The lower lying part of the orchard receives rain water flow from adjacent areas which causes soil erosion. Correlations between yield and crop nutrients and organic matter content were weak (Aggelopoulou et al. 2007).

Data from both years indicate that flesh firmness was lower in the eastern part of the orchard compared to the west side. Fruits with low flesh firmness have a shorter fridge life compared to those with high flesh firmness, and one could ensure these were sent to market separately.

The number of flowers in the spring of 2005 is positively correlated with the yield in the autumn ($r_S = 0.60$ for RC and $r = 0.82$ for FJ). If a map of the number of flowers could be used to predict yield early in the season, this would improve the ability of the farmer and the industry to plan the marketing of fruit. Furthermore, the soluble solids content is negatively correlated with (log) flower number ($r = -0.66$ for RC and $r_S = -0.60$ for FJ), but the correlation with yield is reduced and in the case of RC not significant ($r = -0.33$ for RC and $r_S = -0.46$ for FJ). It would appear that this quality variable is more strongly governed by conditions before flower thinning. Other potential uses of such a map include planning site-specific chemical thinning of flowers, fertilizer application and fruit thinning.

Chemical thinning is applied 10–15 days after blossoming. The effects of chemical thinners on thinning and fruit set are complex and not fully understood. As a first step, chemical thinning could be applied in the parts of the orchard only where the flower numbers are large. Reducing the quantity of chemical used has economic as well as environmental implications.

One fertilizer application strategy would be to apply less fertilizer where flowers are sparse and more where the flowering is greater and trees have higher yield potential. The application of fertilizers in low yielding areas can lead to excess vegetation growth, which increases shading, sensitivity to diseases and competition with flowering the following year. Vegetation growth competes with the creation of flower buds in the summer thereby affecting the yield of the following growing season.

Variation in yield and quality provide a potential for selective harvesting of apples. In areas of the orchard where yield density is high, harvesting could be done in two stages, at each step harvesting only ripe fruit. In low yielding areas, all fruits would be harvested at once.

Conclusions

From the results of the two year experiment in a 0.8 ha orchard we concluded that:

- Significant spatial and temporal variability existed in yield and fruit quality. Global trends in the spatial pattern reflected orchard topography (aspect and light availability). The yield of Red Chief in 2005 showed spatial dependence with an effective range of 35 m, equivalent to about 15 trees along a row.
- No correlation was detected between per tree yield (kg) and average fruit mass (g) of apples for both cultivars in either season, indicating that higher yields were a reflection of larger numbers of fruit.
- Large yields were achieved at some cost in quality. Both yield and flowering were negatively correlated with several fruit quality traits such as flesh firmness, soluble solids and malic acid content, although the patterns were not consistent between cultivars and years. Fruit mass and flesh firmness were negatively correlated with each other for Red Chief.
- The number of flowers per tree was positively and significantly correlated with yield of the related year indicating that yield might potentially be predicted early in the season from maps of flowering.

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References

Aggelopoulou, K. D., Pateras, D., Fountas, S., Gemtos, T. A., & Nanos, G. D. (2007). Soil spatial variability in small Greek apple orchards. In J. V. Stafford (Ed.), *Precision agriculture '07, Proceedings of the 6th European conference on precision agriculture* (pp. 71–78). Wageningen: Wageningen Academic Publishers.

Best, S., Salazar, F., Bastías, R., & León, L. (2008). Crop load estimation model to optimize yield-quality ratio in apple orchards, *Malus Domestica Borkh*, Var. Royal Gala. *Journal of Information Technology in Agriculture*, *3*, 11–18 (e-Journal at www.jitag.org).

Best, S., & Zamora, I. (2008). *Tecnologías aplicable en agricultura de precisión. Uso de Tecnología de Precisión en Evaluación, Diagnóstico y Solución de Problemas Productivos*. Santiago, Chile: Fundacion para la Innovacion Agraria.

Blankenship, S. M., Parker, M., & Unrath, C. R. (1997). Use of maturity indices for predicting poststorage firmness of Fuji apples. *HortScience, 32*, 909–910.

Bramley, R. G. V. (2005). Understanding variability in winegrape production systems. 2. Within vineyard variation in quality over several vintages. *Australian Journal of Grape and Wine Research, 11*, 33–42.

Bramley, R. G. V., & Hamilton, R. P. (2003). Understanding variability in winegrape production systems. 1. Within vineyard variation in yield over several vintages. *Australian Journal of Grape and Wine Research, 10*, 32–45.

Cressie, N. (1993). *Statistics for spatial data, revised version*. New York: John Wiley & Sons.

Delfiner, P. (1976). Linear estimation of nonstationary spatial phenomena. In M. Guarascio, M. David, & C. Hüijbregts (Eds.), *Advanced geostatistics in the mining industry* (pp. 49–68). Dordrecht: Reidel.

Dobermann, A., & Ping, J. L. (2004). Geostatistical integration of yield monitor data and remote sensing improves yield maps. *Agronomy Journal, 96*, 285–297.

Dris, R. (2002). Influence of orchard management on growth and production of fruits. In R. Dris, S. M. Jain, & I. A. Khan (Eds.), *Environment and crop production* (pp. 1–3). Enfield, NH: Science Publishers Inc.

Fountas, S., Blackmore, S., Gemtos, T., & Markinos, A. (2004a). Trend yield maps in Greece and the UK. In M. Vlachopoulou, V. Manthou, L. Illiadis, S. Gertsis, & M. Salampasis (Eds.), *HAICTA 2002: Proceedings of the 2nd international conference on information systems & innovative technologies in agriculture, food and environment* (Vol. 2, pp. 309–319), Thessaloniki: Publishing Center T.E.I. of Thessaloniki.

Fountas, S., Ess, D., Sorensen, C. G., Hawkins, S., Pedersen, H. H., Blackmore, S., et al. (2004b). Farmer experience with Precision Agriculture in Denmark and US Eastern Corn Belt. *Precision Agriculture, 5*, 1–21.

Gemtos, T., Fountas, S., Blackmore, S., & Griepentrog, H. W. (2002). Precision farming in Europe and the Greek potential. In A. Sideridis & C. Yialouris (Eds.), *HAICTA 2002, Proceedings of the 1st Greek conference on information and communication technology in agriculture* (pp. 45–55). Athens: Agricultural University of Athens.

Gemtos, T. A., Markinos, A., & Nassiou, T. (2005). Cotton lint quality spatial variability and correlation with soil properties and yield. In J. V. Stafford (Ed.), *Precision agriculture '05: Proceedings of the 5th European conference on precision agriculture* (pp. 361–368). Wageningen: Wageningen Academic Publishers.

Geovariances. (2008). Structure identification in the intrinsic case. In *Isatis technical reference, Release 8* (pp. 9 − 51). Avon, France: Geovariances. http://www.geovariances.com.

Godwin, R. J., Wood, G. A., Taylor, J. C., Knight, S. M., & Welsh, J. P. (2003). Precision farming of cereal crops: A review of a six year experiment to develop management guidelines. *Biosystems Engineering, 84*, 375–391.

Greer, D. H. (2005). Non-destructive chlorophyll fluorescence and colour measurements of 'Braeburn' and 'Royal Gala' apple (*Malus domestica*) fruit development throughout the growing season. *New Zealand Journal of Crop and Horticultural Science, 33*, 413–421.

Griffin, T. W., Lowenberg-DeBoer, J., Lambert, D. M., Peone, J., Payne, T., & Daberkow, S. G. (2004). *Adoption, profitability, and making better use of precision farming data*. Staff Paper #04-06. USA: Department of Agricultural Economics, Purdue University.

Hastings, A. (2004). Transients: the key to long-term ecological understanding? *Trends in Ecology & Evolution, 19*, 39–45.

Isagi, Y., Sugimura, K., Sumida, A., & Ito, H. (1997). How does masting happen and synchronize? *Journal of Theoretical Biology, 187*, 231–239.

Lakso, A. N., & Robinson, T. L. (1997). Principles of orchard systems management optimizing supply, demand and partitioning in apple trees. *Acta Horticultura, 451*, 405–415.

López-Granados, F. L., Expósito, M. J., Álamo, S., & García-Torres, L. (2004). Leaf nutrient spatial variability and site-specific fertilization maps within olive (*Olea europaea L.*) orchards. *European Journal of Agronomy, 21*, 209–222.

Maletti, G. M., & Wulfsohn, D. (2006). Evaluation of variance models for fractionator sampling of trees. *Journal of Microscopy, 222*, 228–241.

Mandallaz, D. (2000). Estimation of the spatial covariance in Universal kriging: Application to forest inventory. *Environmental and Ecological Statistics, 7*, 263–284.

Marcotte, D., & David, M. (1988). Trend surface analysis as a special case of IRF-k kriging. *Mathematical Geology, 20*, 821–824.

Markinos A., Gemtos T. A., Toulios L., Pateras D., Zerva G., & Papaeconomou, M. (2004). The influence of cotton variety in the calibration factor of a cotton yield monitor. In M. Vlachopoulou, V. Manthou, L. Illiadis, S. Gertsis, & M. Salampasis (Eds.), *HAICTA 2002: Proceedings of the 2nd International conference on information systems & innovative technologies in agriculture, food and environment* (Vol. 2, pp. 65–74). Thessaloniki: Publishing Center T.E.I. of Thessaloniki.

Marquina, P., Venturini, M. E., Oria, R., & Nequerela, A. I. (2004). Monitoring colour evolution during maturity in Fuji apples. *Food Science and Technology International, 10*, 315–321.

McGuire, R. G. (1992). Reporting of objective color measurements. *HortScience, 27*, 1254–1255.

Pelletier, G., & Upadhyaya, S. K. (1999). Development of a tomato load/yield monitor. *Computers and Electronics in Agriculture, 23*, 103–107.

Pozdnyakova, L., Gimenez, D., & Oudemans, P. V. (2005). Spatial analysis of cranberry yield at three scales. *Agronomy Journal, 97*, 49–57.

Rao, C. (1971). Minimum variance quadratic unbiased estimation of variance components. *Journal of Multivariate Analysis, 1*, 445–456.

Roel, A., & Plant, R. E. (2004a). Factors underlying yield variability in two California rice fields. *Agronomy Journal, 96*, 1481–1494.

Roel, A., & Plant, R. E. (2004b). Spatiotemporal analysis of rice yield variability in two California fields. *Agronomy Journal, 96*, 77–90.

Sakai, K., Noguchi, Y., & Asada, S. (2008). Detecting chaos in a citrus orchard: Reconstruction of nonlinear dynamics from very short ecological time series. *Chaos Solitons & Fractals, 38*, 1274–1282.

Taylor, J. A. (2004). *Digital terroirs and precision viticulture: Investigations into the application of information technology in Australian vineyards*. Unpublished PhD dissertation, The University of Sydney, New South Wales, Australia.

Vasilakakis, M. (2004). *General and specialized pomology*. Thessaloniki: Gartaganis Publications.

Wackernagel, H. (2003). *Multivariate geostatistics* (3rd ed.). Berlin: Springer-Verlag.

Wulfsohn, D., Maletti, G. M., & Toldam-Andersen, T. B. (2006). Unbiased estimator of the number of flowers on a tree. *Acta Horticulturae, 707*, 245–252.

Yanai, J., Choung, K. L., Kaho, T., Iida, M., Matsui, T., Umeda, M., et al. (2001). Geostatistical analysis of soil chemical properties and rice yield in a paddy field and application to the analysis of yield-determining factors. *Soil Science and Plant Nutrition (Japan), 47*, 291–301.

Ye, X., Sakai, K., Manago, M., Asada, S., & Sasao, A. (2007). Prediction of citrus yield from airborne hyperspectral imagery. *Precision Agriculture, 8*, 111–125.

Zaman, Q., & Schuman, A. W. (2006). Nutrient management zones for citrus based on variation in soil properties and tree performance. *Precision Agriculture, 7*, 45–63.

Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture—a worldwide overview. *Computers and Electronics in Agriculture*, *36*, 113–132.