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RESEARCH ARTICLE

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Nitrogen replenishment using variable rate application technique in a small hand-harvested pear orchard

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Abstract

Precision agriculture is a management approach for sustainable agriculture. It can be applied even in small fields. It aims to optimize inputs, improve profits, and reduce adverse environmental impacts. In this study, a series of measurements were conducted over three growing seasons to assess variability in a 0.55 ha pear orchard located in central Greece. Soil ECa was measured using EM38 sensor, while soil samples were taken from a grid 17 × 8 m and analysed for texture, pH, P, K, Mg, CaCO3, and organic matter content. Data analysis indicated that most of the nutrients were at sufficient levels. Soil and yield maps showed considerable variability while fruit quality presented small variations across the orchard. Yield fluctuations were observed, possibly due to climatic conditions. Prescription maps were developed for nitrogen variable rate application (VRA) for two years based on the replacement of the nutrients removed by the crop. VRA application resulted in 56% and 50% reduction of N fertiliser compared to uniform application.

Additional keywords: precision agriculture; yield mapping; soil variability; site-specific management; fertilisation; *Pyrus communis* L.

Abbreviations used: CV (coefficient of variation); ECa (apparent soil electrical conductivity); EM (electromagnetic induction); ETc (crop evapotranspiration); FF (flesh firmness); GHG (greenhouse gas); ME (mean error); NUE (nitrogen use efficiency); OM (organic matter); PA (precision agriculture); RMSE (root mean square of standardised error); SSC (soluble solids content); SSCM (site-specific crop management); VRA (variable rate application).

Authors' contributions: AV performed the experiments, analysed the data and wrote the paper. GDN contributed in the data analysis and reviewing of paper, SF in the discussion part and reviewing the paper, JB in the experimental process, AC in geostatistic analysis, TAG in the general concept of the paper, the design of the experimental protocol and in reviewing the paper.

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Introduction

Site-specific crop management (SSCM) within management zones aims to match resource application and agronomic practices to soil and crop requirements (Whelan & McBratney, 2001). Two methods of implementing SSCM for variable rate application (VRA) of crop inputs are used: sensor-based and map-based management zones (Zhang *et al.*, 2002). The sensor-based approach uses real-time sensors in an 'on-the-go' fashion, to measure the desired properties, such as soil and plant properties, and controls variable rate applicator based on these measurements, without necessarily using a positioning device (Zhang *et al.*, 2002; Holland & Schepers, 2013). Alternatively, developing management zones and then prescription and application maps, based on historical data, can be the basis for variable rate inputs applications. Compared to the sensor-based approach, which uses expensive sensors, management zone maps are more economical (Zhang *et al.*, 2002). The development of VRA maps has been widely based on laboratory measurements of spectral reflectance of soil or crops (Daniel *et al.*, 2004), or hand-held device measurements (Liakos, 2013), aerial photography images (Fleming *et al.*, 2000; Zaman & Schuman, 2006) and satellite observations (Li *et al.*, 2008; Guo *et al.*, 2012). Spatial variability in yields has also been considered as a useful indicator to determine variable rate nutrient management (Johnson *et al.*, 2003). According to Heege (2013), if yields are recorded during harvest over small areas and georeferenced at a very fine spatial resolution, then nutrient removal for these small areas can be determined. Then the nutrients can be applied in a site-specific way as replacement of the removed nutrients by the yield. Two prerequisites for this site-specific application are soil nutrient adequacy at the beginning of the application and that losses of nutrients by leaching and runoff of water or erosion did not occur or could be predicted (Heege, 2013). A N prescription map based on nutrient removal by the fruit was created for an apple orchard by Aggelopoulou *et al.* (2011). They claimed that if N was applied site-specifically, 38% of N could be saved compared to uniform application. However, this study only showed the theoretical savings, without a real application in the field. Liakos *et al.* (2013) applied variable and uniform rates in alternate rows in an apple orchard and found that the amount of fertiliser used in VRA treatments was reduced by 32.4%, while the farmer's profit increased by 21%. In a similar study Zaman *et al.* (2005) found that N-VRA resulted in a 40% cost reduction for fertilisation in citrus orchards.

Environmental and economic benefits of VRA are thought to increase due to the relative increases in fertiliser use efficiency as compared with uniform application (Batte & Arnholt, 2003). VRA of fertiliser may increase fertiliser use efficiency and reduce nitrogen losses through reduction in ammonia volatilization (López Bellido *et al.*, 2012). At field scale, when soil organic and inorganic N pools are in steady state, nitrogen use efficiency (NUE) refers to the amount of yield per unit of added N, or the proportion of applied N that is removed in harvested biomass (Robertson & Vitousek, 2009). To minimize N loss from cropped fields, agronomists promote a 4R strategy for managing N (IFA, 2009): applying N at the right rate, at the right time, in the right place, and in the right formulation. However, the main factor affecting NUE is the rate of applied N, where N losses increase rapidly when N inputs exceed the crop assimilation capacity (Schlegel *et al.*, 1996; Dobermann *et al.*, 2006). The effects of N timing, N formulation, and N placement are also important, but usually produce smaller improvements in NUE compared to optimizing N rate (Power & Schepers, 1989). Uniform fertiliser application can result in nutrient uptake as low as 30% of applied fertiliser. The remaining 70% has the potential to leach into groundwater or to be lost due to surface runoff or volatilization (Legg & Meisinger, 1982). Wang *et al.* (2003) found that switching from uniform application to VRA of fertiliser resulted in reduction of nutrient loss due to surface runoff.

The majority of VRA technology has been implemented in arable crops, and only a small number of studies concerned VRA in orchards implementing one year of variable application (Zaman *et al.*, 2005; Fountas *et al.*, 2011). The most extensively studied subject has been N fertility level, as N application has the highest economic and environmental impact. The focus on N application is quite probably due to the fact that local over-fertilisation may increase nitrate leaching and thus decrease ground water quality, may induce ammonia volatilization and nitrous oxide emissions leading to increased greenhouse gas (GHG) emissions as well as soil acidification (Basso *et al.*, 2012). Moreover, the focus on N application may be due to the high cost of N fertilisers coupled with the significant environmental impact of N fertiliser production.

Research in small-size hand-harvested orchards (Gemtos *et al.*, 2013; Zude-Sasse *et al.*, 2016), including apples (Aggelopoulou *et al.*, 2010; Liakos *et al.*, 2013) and peaches (Ampatzidis *et al.*, 2009), proved that variability was present even in small-size fields. Konopatzki *et al.* (2012) investigated the spatial variability of yield and soil properties in a hand-picked pear orchard, resulting in low correlations between yield and soil properties. Perry *et al.* (2010) analyzed spatial variability in pears by measuring yield and tree attributes and resulted in strongly spatially clustered data, suggesting differentiation of management in distinct zones.

Taking into account the limited number of studies for the application of Precision Agriculture (PA) and VRA techniques in small orchards, the aim of the present study was to assess the variability of soil, yield and fruit quality in a small hand-harvested pear orchard and to estimate the potential benefits of variable rate nitrogen application using the replenishment strategy.

Material and methods

Field description

The study was carried out in a 0.55-ha pear (*Pyrus communis* L.) cv. 'Coscia' orchard on flat terrain in Tirnavos, located in the Thessaly region, Central Greece (WGS84: 22º 16´80´´E, 39º44´10´´N, elevation 88 m). The orchard was planted in 1994 with the early maturing pear cultivar Coscia grafted onto BA29 quince rootstock. The trees were trained as 5 floor palmette. Tree spacing was 4 m between rows and 3.5 m intra-row. The orchard was managed conventionally by the farmer, although there was a tendency to apply only the necessary practices in order to reduce inputs and costs. The farmer usually applied fertiliser in several doses during the growing season. Almost 47% of N fertilisation was applied as basic fertilisation at the end of February or early March. The remaining 53% of N was applied in 2 to 5 doses from early May until the end of June by fertigation. Drip irrigation was used from mid-April to mid-September with frequency depending on the weather conditions. About 5.3 m^3 of water per tree were applied every year (about 3820 m^3/ha/year) (Table 1). Weed control was performed four times every year with weed mowing between the rows and contact herbicides on the row. Crop protection for pests and diseases was applied according to the guidelines from the local co-operative. Winter pruning was performed for the first and second year shoots in late February or early March. Full bloom was recorded at the beginning of April for all the studied years (5th, 2nd and 1st of April in 2011, 2012 and 2013, respectively). Fruitlet hand thinning was performed in May. Harvesting was conducted during the second half of July by hand picking and placing the fruits in plastic bins along the rows. In the present study, three-year yield measurements were conducted. Rainfall was 405 mm in 2011, 609 mm in 2012 and 461 mm in 2013. The average temperature, relative humidity and rainfall for the three years are presented in Fig. 1 and in Table 1 the annual ETc, rainfall and applied irrigation water.

Measurements

Soil apparent electrical conductivity (ECa)

In order to assess the field variability at a fine spatial scale, ECa was initially measured in September 2010 using an EM-38 instrument (EM38 RT, Geonics LTD, Ontario, Canada). Vertical dipole mode was recorded. The instrument was carried out manually by an operator between the rows. A DGPS receiver (Differential-GPS 106, Trimble Ltd., USA) was used to record the position and the measurement on the go and a data logger was used to store the data every one second (Allegro CX, Jupiner Systems Inc., Logan, UT, USA).

EM38 measures apparent EC that is mainly an indication of soil texture when measurements are taken at near field capacity water content. Therefore, ECa maps indicate soil texture variability. ECa often, but not always, is related to crop yield (Corwin & Lesch, 2005). However, this relationship is quite complex and usually not linear. It is assumed that fertigation on the row affect nutrients but not texture.

Soil analysis

Soil cores up to 300-mm depth were taken in March 2010 every 5 trees on the row in the midpoint between trees and every two rows, forming a grid of 17 × 8 m. Forty samples were taken (Fig. 2), air-dried, passed through a 2 mm sieve and analysed for the following properties: soil texture (% sand, % silt and % clay), organic matter (OM, %), pH, phosphorus (ppm), calcium carbonate (%), exchangeable potassium (ppm) and exchangeable magnesium (ppm). All soil characteristics were measured only once at the beginning of the experiment. Soil texture was measured by Bouyoukos densimeter; soil OM was measured with Walkley-Black method; soil pH was determined in a 1:1 water solution; P concentration was measured by Olsen method; $CaCO_3$ was measured with Bernard method; exchangeable K and Mg were measured using ammonium acetate method (Page *et al.*, 1982). The critical limits of soil parameters were based on IFA (1992) as they have been modified and adapted for Greek conditions by Koukoulakis (1995). Thus, medium soil OM rages from 1.8 to 2%, adequate P rages from 17 to 25 ppm, adequate K rages from 140 to 200 ppm, adequate Mg rages from 66 to 120 ppm and adequate $CaCO_3$ rages from 2.1 to 5%.

Table 1. Annual precipitation, irrigation and ETc

Year	Precipitation (mm/yr)	Irrigation (m^3/ha·yr)	Annual ETc (mm/yr)
2011	405	3890	762
2012	609	3750	862
2013	461	3820	763

Yield mapping

Pears were hand harvested and placed in plastic bins along all the tree rows. The bins collected from a group of five adjacent trees were weighed to give the yield per five trees for yield mapping. The geographical position of the middle tree in the group was recorded using a GPS (Garmin Etrex Legend H, Kansas, KS, USA), with differential correction (ca. 0.5 m accuracy), connected with a hand-held computer, so forming a grid of 17 x 4 m cells. Harvesting was carried out during the second half of July in 2011, 2012 and 2013, in one or more passes depending on the yield of each year.

Fruit quality mapping

In 2011 and 2012 before harvest, pear fruit samples were collected at 40 georeferenced locations, next to the soil samples (soil samples were taken in the midpoint between trees) in almost the same soil sample points forming a grid of 17 × 8 m, since the sampling was performed row by other row. At each location (group of five trees), two fruits were randomly selected from each side of the point where the soil was sampled, and the

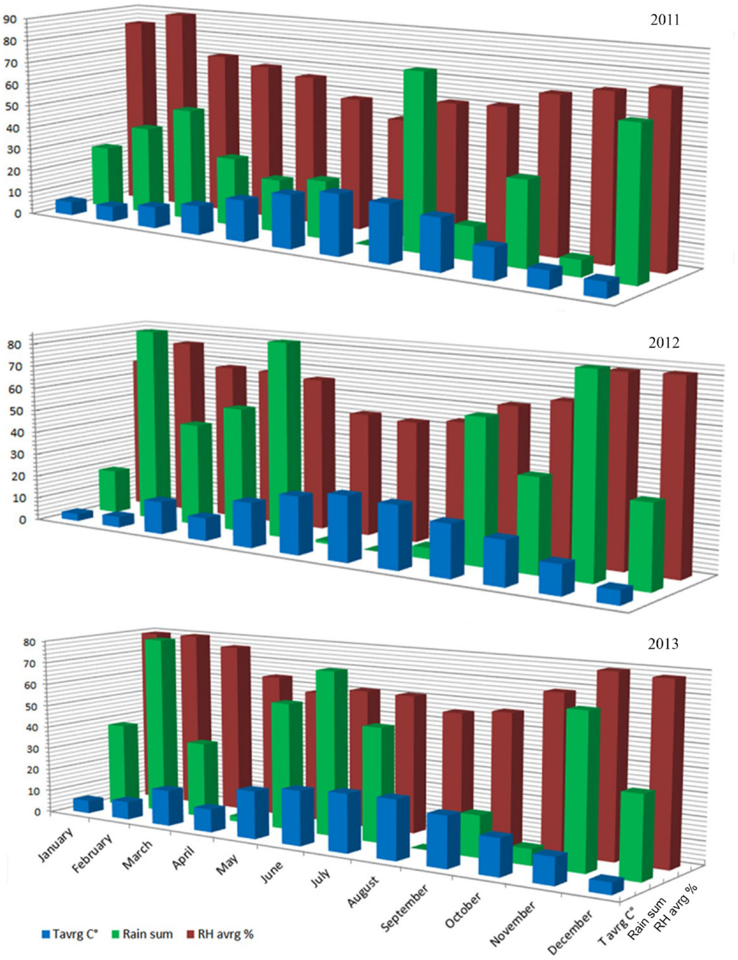

Figure 1. Monthly weather conditions during 2011, 2012 and 2013: average temperature in °C (Tavrg C°), monthly rainfall in mm (Rain sum) and average relative humidity in % (RH avrg%)

following quality properties were measured per fruit:

–Fruit weight.

–Skin colour with a Minolta chroma meter (Model CR-400, Minolta Ltd, Osaka, Japan). The device was calibrated before use with a white tile. The colour parameters L*, a*, b*, were measured. The parameters L* and a* are more significant for pears, since L* gives the brightness (L* =0, black colour; L* =100, white colour) and a* defines accurately the fruit skin green colour (a*> 0, red colour; a*< 0, green-blue colour). Two sides of each pear fruit were sampled and an average value was measured.

–Flesh firmness (FF) after skin removal, using a Turoni penetrometer with 8 mm diameter plunger (Model 53205, Turoni Srl, Forli, Italy). The mean of two measurements taken from opposite sides of each sampled fruit was calculated.

–Soluble solids content (SSC) on juice squeezed from each fruit (expressed in g of soluble solids per 100 g of juice) using an Atago refractometer (Model PAL-1, Atago, Japan).

–Juice pH with a Hanna pH-meter (Model HI 9024, Hanna Instruments, Amorin, Portugal).

–Juice acidity by titration (expressed in g of malic acid per 100 g of juice) with 0.1 N NaOH to an endpoint of pH 8.2 with Hanna pH-meter (Model HI 9024, Hanna Instruments, Amorin, Portugal).

Nitrogen site-specific application

In early March 2012 and 2013, N-VRA for the basic soil fertilisation was carried out, using a low rate nitrogen release fertiliser (ammonium sulphate). The site-specific application was performed by hand at each group of five trees (equal amount for each tree of the group). The replenishing amount of N was calculated from the N that was removed by the previous year's yield from each group of five trees. Given that the field was flat, run off from erosion effects on nutrient losses were taken as negligible. Prescription maps were then developed. This replenishment approach was suggested by Aggelopoulou *et al.* (2011) and Heege

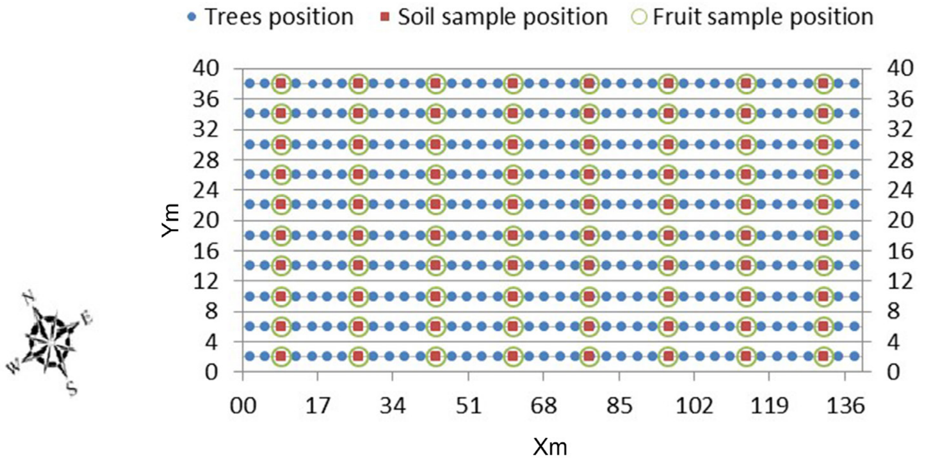

Figure 2. Trees (in blue), soil sample positions (in red) and fruit sample positions (in green) in the orchard.

(2013) and was practically applied in an apple field by Liakos *et al.* (2013). According to Aggelopoulou *et al.* (2011), the suggested theoretical replenishment of N in an apple orchard was based on the previous year's yield and estimated according to IFA (1992). Aggelopoulou *et al.* (2011) developed an N prescription map in spring with three management zones based on the removed N by the yield, plus 30% losses. They suggested to apply basic N quantity uniformly in early summer (160 g of N per five trees), and site-specifically at three rates (130, 260 and 390 g) of N per five trees in spring. The methodology of N application in the studied pear orchard was based on Aggelopoulou *et al.* (2011) methodology, while the estimation of the fertiliser amount for pears was based on literature data of pear cultivation (IFA, 1992), where it is indicated that 31 kg N/ha was removed by 25 Mg/ha fruit yield and the prunings in a pear orchard. The prunings were also added as the farmer removed them outside the field. Based on this, 25.1 kg N/ha were removed from the soil by 20.23 Mg/ha yield in 2011, and 38 kg N/ha were removed by 30.6 Mg/ha yield in 2012. The early spring basic fertilisation was variably applied, while the subsequent N applications were applied uniformly in the field by fertigation. The early spring applied N was used for spring vegetative growth (and thus flower bud formation for next year's crop) and fruitlet growth, while the late spring/early summer applied N by the drip irrigation system uniformly was used mainly for fruit growth (Sánchez, 2002).

Data analysis

Exploratory data analysis was carried out to obtain initial descriptive statistics and Pearson's correlation to assess correlations between the studied variables, and linear regression coefficient to address the quality of the model. SPSS software (SPSS Inc., Release 17.0., Chicago, USA) was used for the analysis.

In order to avoid performing interpolation of the measurements, the largest grid among all measurements was selected and all the variables were transformed accordingly. Soil and quality sampling was the largest grid used (17 × 8 m, leading to a total of 40 cells of 135.7 m^2 each) and was therefore taken as the reference grid for all subsequent data analysis. Consequently, the measurements of yield were transformed to the 40-cell grid by merging the two yield grid cells corresponding to the main 40-cells grid and calculating the mean values. The GIS software package (ArcGIS, ESRI, Inc., USA) was used to calculate the mean values for the measured parameters in each of the 40-grid cells. The selected 17 × 8 m grids were formed and the measured variables (points) for each variable were calculated using the mean function to calculate the mean values of the points included in each grid cell (Tagarakis *et al.*, 2013).

According to the literature, delineation of productivity or management zones is generally recommended to vary from 2 to 5 parcels (Fraisse *et al.*, 2001). Considering the small size of the pear orchard under study (0.55 ha), dividing it into more than 2 or 3 zones was not practical as the resulting parcels would be too small for management. Therefore, all measured parameters were classified into 2 classes of equal number of cells designated as high and low values (two iso-frequency classes) for the development of homogeneous zone maps for each variable. Tagarakis *et al.* (2013) followed a specific procedure in vines to examine which parameters were better candidates for delineating yield and grape quality management zones. Each cell of a single characteristic variability map was matched with the same cell on the yield map (Fig. 3). The overall

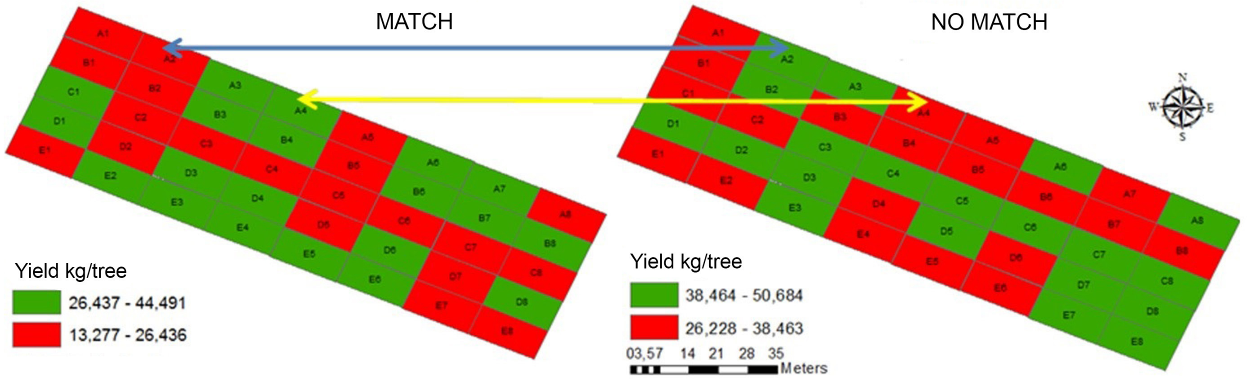

Figure 3. Example of the zone map cell analysis following Tagarakis *et al*. (2013)

accuracy statistic was calculated using the number of matching cells between maps (*i.e.* belonging to the same class) divided by the total number of cells (40 cells), providing an index of the overall accuracy, *i.e.* a degree of spatial association (agreement) between the compared data. In the current study, the same procedure was followed to observe the degree of agreement between yield maps, especially after performing N-VRA, as well as to find out which attributes were better spatially associated to yield maps.

In order to test the occurrence of spatial association within the field and to assess the scale of such association, an experimental variogram of ECa was calculated. This variable was selected among the other soil parameters because of the number of numerousness, which allowed estimating a reliable variogram model. An authorised mathematical function was then fitted to the experimental variogram according to least squares criteria. The optimal model was selected through cross-validation on the basis of two particular statistics: mean error (ME), whose optimal value is zero, as an indicator of bias of estimation, and root mean square of standardised error (RMSE), whose optimal value is one, as an indicator of accuracy of estimation (Carroll & Cressie, 1996). Moreover, ECa was preferred to the other soil parameters because it can be used as a synthetic indicator of multivariate spatial variation of the field, as widely shown in the scientific literature (Corwin & Lesch, 2005; Castrignanò *et al.*, 2012).

Results

Descriptive statistics for the yield, soil and fruit quality properties using the original data are summarized in Table 2. The coefficient of variation (CV) showed that yield (kg per tree) variation in 2011 was considerable, decreased in 2012 and increased again in 2013. ECa, for the whole orchard, showed a small variation ranging from 10.88 mS/m to 24.50 mS/m with CV equal to 13%. Moreover, the ECa data for the entire orchard, were assumed normally distributed as tested by the values of skeweness (0.52) and kurtosis (3.29) and median value (16.63 mS/m) quite close to the mean (16.99 mS/m) (Table 2). As far as soil properties are concerned, clay and P had the largest spatial variation and silt the smallest. Soil analysis showed that silt was dominant (64%) in the soil texture followed by sand (35%) and clay (5%) (Table 2). According to the USDA-NRCS Soil Taxonomy System (1998), the soil is classified as silt-sandy, light soil. Results for soil pH, which ranged from 7.43 to 8.67, indicated an alkaline soil in which soil P and other metals are largely not available to plant roots (especially when pH increases above 8). Soil OM ranged from low to almost high values. P ranged from very low to excess values. Soil $CaCO_3$ concentration was low to adequate. Soil K was found to be below adequate concentrations and Mg ranged from low to adequate concentrations. Most of the variables measured had near normal distributions ($-1 < \text{Skewness} < 1$).

For the crop yield data during the three years of study, a strong correlation was detected between yields for the low yielding years 2011 and 2013 ($r = 0.616$, $p<0.01$) (Table 3). Correlation between ECa and yield was not found. Yields for 2011 and 2013 were negatively correlated with OM and K, and positively correlated with Mg concentration (Table 3). Furthermore, 2013 yield was also negatively correlated with P and positively with soil pH. Yield for 2012 was only correlated with clay. Among soil properties, the strongest correlations appeared between K and Mg ($r = -0.664$, $p<0.01$).

An experimental variogram of ECa was calculated. Since ECa data distribution did not show large departures from normal distribution, except few high values, the data were not submitted to any transformation after filtering the outliers (differing from the mean more than

Table 2. Descriptive statistics for yield 2011, 2012 and 2013, soil properties and quality characteristics

Descriptive	Min	Max	Mean	SD	CV%	Skewness
Yield (kg/tree)						
2011	13.28	44.49	25.87	5.62	21.72	0.51
2012	26.23	50.68	38.65	6.78	17.54	-0.04
2013	10.13	36.11	20.40	5.42	26.58	0.42
Soil properties						
ECa (mS/m)	10.88	24.50	16.99	2.27	13.36	0.52
OM (%)	0.41	2.67	1.62	0.63	39.06	-0.62
Sand (%)	26.13	43.44	32.02	5.49	17.15	0.77
Silt (%)	51.57	72.07	63.82	5.32	8.34	-0.27
Clay (%)	0.72	13.05	4.17	4.36	104.69	0.76
P (ppm)	1.04	26.98	10.13	7.44	73.52	0.92
K (ppm)	55.23	144.19	79.53	23.42	29.45	1.41
Mg (ppm)	11.12	100.18	67.05	24.31	36.26	-0.98
$CaCO_3$ (%)	0.70	2.26	1.21	0.34	28.22	1.26
Quality characteristics						
2011						
L *	59.02	65.30	61.58	1.55	2.52	0.43
a *	-8.29	-3.92	-7.22	0.86	11.90	1.62
FF (N)	50.47	77.37	63.00	5.81	9.22	0.46
SSC (%)	10.85	13.95	12.40	0.75	6.03	0.21
Malic acid (%)	1.26	2.43	1.73	0.29	16.73	0.61
2012						
L *	67.08	72.49	69.63	1.46	0.10	-0.93
a *	-9.85	-4.75	-8.55	0.91	10.65	0.10
FF (N)	47.82	59.68	53.56	2.88	5.38	0.27
SSC (%)	10.80	13.95	12.03	0.74	6.15	0.56
Malic acid (%)	1.26	2.09	1.57	0.20	12.61	0.26

Number of georeferenced sampling points (N = 40); ECa: apparent soil electric conductivity; OM: organic matter; FF : flesh firmness; SSC: soluble solids content; SD: standard deviation; CV: coefficient of variables

2.5 SD) and the values corresponding to malfunction of GPS. An isotropic nested model was fitted to the experimental variogram (Fig. 4) consisting of three basic spatial structures: nugget effect (corresponding to erratic component of variance); spherical model with range of 4.29 m and spherical model with range of 31 m, the last two corresponding to spatially structured components of variance. The results of cross-validation show that prediction is unbiased (ME=0.0028 mS/m) and accurate (root RMSE=0.97). The shorter range (4.29 m) is related to the geometrical arrangement of the trees, whereas the longer range (31 m) is an indicator of the scale of spatial dependence occurring within the field.

Yield, ECa and soil characteristic maps are presented in Figs. 5 and 6. Following the methodology explained in materials and methods section (data analysis) concerning the degree of agreement between yield maps, it was found that, among yield maps the highest degree of similarity was between 2011 and 2013 yield maps (70% degree of agreement) (Table 4). The 2012 yield map (after performing the first VRA) had also a substantial degree of similarity (50%) with the 2013 yield map (after the second VRA). Among the soil parameters, silt, pH, $CaCO_3$ maps were more similar to the 2013 yield map, while only silt showed high similarity with the 2011 yield.

Table 3. Correlation matrix between yield and soil properties

	Yield 2011	Yield 2012	Yield 2013	ECa	pH	P	K	Mg	Ca	$CaCO_3$	OM	Sand	Silt	Clay
Yield 2011	1													
Yield 2012	-0.174	1												
Yield 2013	0.616**	-0.226	1											
ECa	0.046	-0.218	0.104	1										
pH	0.146	-0.036	0.338*	0.061	1									
P	-0.241	-0.105	-0.363*	-0.191	-0.262	1								
K	-0.399*	0.021	-0.466**	0.449**	-0.267	0.083	1							
Mg	0.317*	-0.118	0.496**	-0.205	-0.040	-0.107	-0.664**	1						
Ca	-0.033	0.234	-0.364*	-0.297	-0.389*	0.045	0.020	-0.232	1					
$CaCO_3$	0.180	0.026	0.280	0.173	0.149	-0.463**	-0.337*	0.095	-0.224	1				
OM	-0.470**	-0.018	-0.368*	0.068	-0.144	0.323*	0.367*	-0.415**	-0.404**	0.003	1			
Sand	-0.029	-0.167	-0.092	0.034	-0.042	-0.259	-0.132	0.050	0.233	0.228	-0.224	1		
Silt	0.185	-0.085	0.150	0.263	0.194	0.144	0.330*	-0.177	-0.343*	-0.112	0.121	-0.674**	1	
Clay	-0.190	0.314*	-0.067	-0.364*	-0.184	0.150	-0.237	0.153	0.125	-0.151	0.136	-0.436**	-0.371*	1

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed). ECa: apparent soil electric conductivity; OM: organic matter

Likewise, clay and K maps showed high similarity with 2012 yield.

Fruit quality variables showed small variation (Table 2) in both years (2011 and 2012). Quality maps for 2011 and 2012 are presented in Fig. 7 and 8, respectively. In 2011 (before N-VRA) fruit quality variables FF and SSC showed a small to moderate negative correlation with 2011 yield ($r_{yield/FF}$=-0.324, p=0.05, $r_{yield/ssc}$=-0.467, p<0.01), *i.e.* as yield was moderate to low, fruits were of high organoleptic quality. Fruit malic acid concentration in the same year showed positive correlation with FF and SSC, but negative with pH and skin L* variable. These correlations are related to fruit maturity and high organoleptic quality. Quality variables in 2012 were not related with yield and only the malic acid concentration showed moderate positive correlations with FF, but negative ones with the two skin colour parameters L* and a* ($r_{malic/FF}$=0.446, p<0.01, $r_{malic/L*}$=-0.464, p<0.01, and $r_{malic/a*}$=-0.343, p<0.05) related to fruit maturity. Since fruit quality (and maturation) is generally associated mainly with climate and soil conditions, tree characteristics and cultural practices, and secondly with yield, as found in this study, the correlation patterns were not consistent among the years.

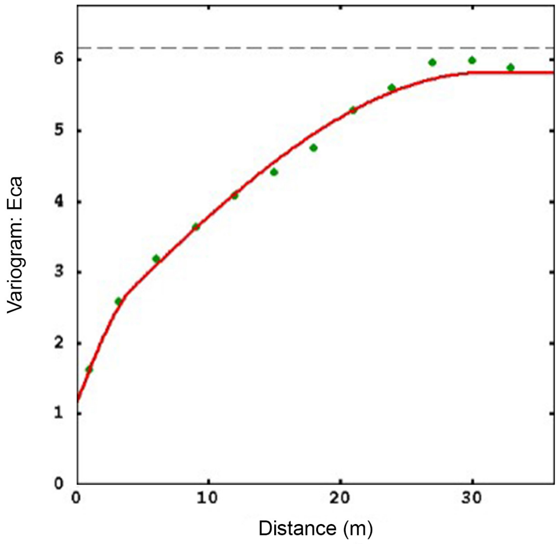

Figure 4. Variogram of the ECa data

Nitrogen site-specific application

In crop season 2011-2012, 25.1 kg N /ha was removed from the soil in a pear orchard with total 20.23 Mg/ha yield. This quantity of N represents the total uptake from the fruit and prunings (the farmer removed the prunings from the field). The yield of

Table 4. Percentage of similarity between the variables when classified into two zones based on Tagarakis *et al.* (2013) methodology

	Yield 2011	Yield 2012	Yield 2013
Yield 2011	100	30	70
Yield 2012	30	100	50
Yield 2013	70	50	100
ECa	55	55	55
OM	35	50	35
Sand	55	40	45
Silt	60	45	70
Clay	45	60	55
K	40	60	35
Mg	55	40	55
P	45	40	35
pH	55	55	80
$CaCO_3$	55	52.5	75

ECa: apparent soil electric conductivity. OM: organic matter.

2011 per five trees ranged from 52.5 to 270.8 kg, which corresponds to the quantity of N removed from the soil varying between 65 and 335 g per five trees. The amount of N applied by fertigation uniformly in the pear orchard under study in 2012 was 65 g per five trees, which was the minimum quantity of N removed from the soil. The rest of N removed from the soil varied from 0 to 270 g per five trees. With 66% efficiency of basic N application, due to leaching from late rainfalls and losses to the air, the amount of fertiliser applied as basic fertilisation in 2012 ranged from 0 to 405 g per five trees. That amount was divided into three equal doses of 135 g and the three application rates were defined at 135 g N, 270 g N and 405 g N. The same methodology was followed in order to create the N application map of the year 2013, based on the yield of 2012. The application maps of both years are shown in Fig. 9. The total amount of N in the form of $(NH_4)_2SO_4$ as basic fertilisation applied in 2012 was 28.18 kg N/ha (160 kg $(NH_4)_2SO_4$/ha) and 38.182 kg N/ha (181.82 kg $(NH_4)_2SO_4$/ha) in 2013.

Discussion

The yield pattern of the experimental years 2011, 2012 and 2013 was quite different. A strong correlation between the yields of 2011 and 2013 was detected which was also proved from the highest degree of similarity between 2011 and 2013 yield maps. In 2012 season, when the first VRA of basic N fertilisation took place, the minimum yield per tree increased, while the maximum tree capacity remained almost at the same level. It was expected that the application of N site-specifically in 2012 season would reduce the variability of yield of the same year and that proved true according to CV presented in Table 2. In 2013 season, however, even though the second N-VRA took place, the overall yield decreased and yield variability increased again probably due to a combination of climatic conditions and soil water availability. Inadequate rain and irrigation water availability, mainly in April (Fig. 1), negatively affected tree physiology in such a way that leaves were not functioning properly due to lack of water, carbohydrates were limited and fruitlet drop rate increased (based on field observations) (Webster, 2002). The result for the orchard under study (as well as for other orchards of the same cultivar in the area) was substantial flower and early fruitlet drop in April and early May of 2013, resulting in changes in the yield pattern at harvest. It is evident that more factors than fertilization affect yield variability and further investigation is required for more solid conclusions.

Fruit quality variability was low for both years. Comparison of the fruit quality properties maps for both years, 2011 and 2012, showed substantial degree of similarity ranging from 50% to 60%. Comparing the cells of yield and quality maps, there was a tendency for the high yield to be associated with low values of quality parameters, a result previously found for apples by Aggelopoulou *et al.* (2010) and Gemtos *et al.* (2013) and Ystaas (1990) for pears. Low values for quality parameters (except FF and malic acid concentration) are associated with delayed maturation (deeper green skin colour with lower L* and a* values, lower SSC and pH, higher FF and malic acid concentration) or inferior quality (deeper green skin colour with lower L* and a* values, lower SSC, pH and FF and higher malic acid concentration) (Kader, 2002). Also, VRA of N did not influence pear fruit quality as Ystaas (1990) had found for another pear cultivar.

The amount of N fertiliser the farmer usually applies when the same pear orchard is managed conventionally was compared to the amount of N applied according to the proposed methodology to assess the savings. Regarding N basic fertilisation with $(NH_4)_2SO_4$ applied in early spring, the farmer used a uniform rate of 0.5 kg of the fertiliser for each tree, adding a total amount of 200 kg of $(NH_4)_2SO_4$ (42 kg N) in the pear orchard of 0.55 ha [363.64 kg $(NH_4)_2SO_4$/ha, 76.4 kg N]. The N-VRA resulted in 56% and 50% savings in 2012 and 2013, respectively, without negatively affecting yield. Several studies stated that N fertiliser rate can

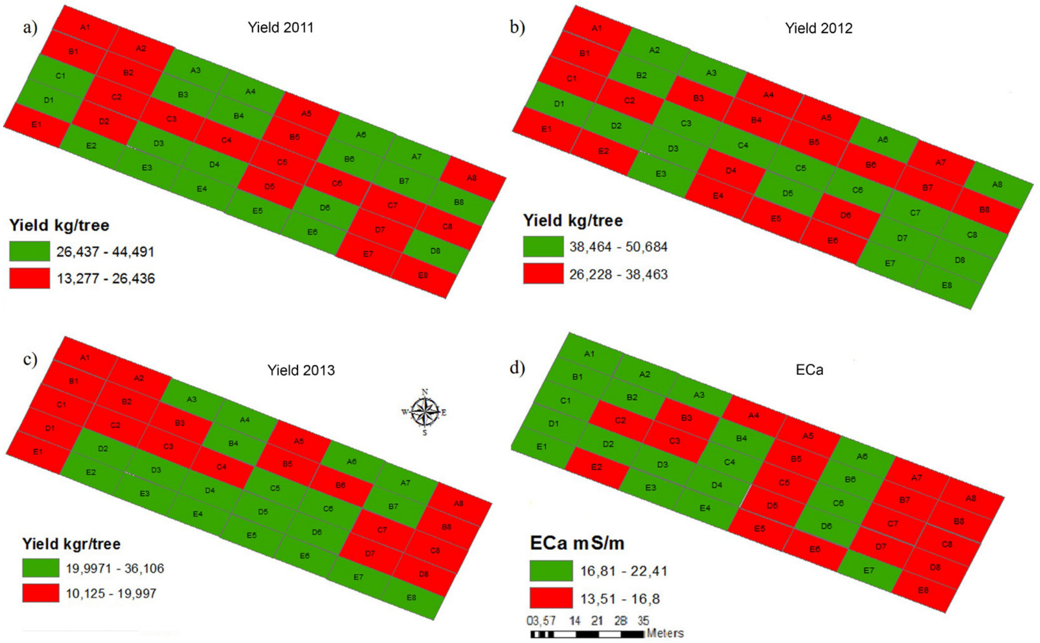

Figure 5. Yield maps for 2011 (a), 2012 (b) and 2013 (c) and ECa (d)

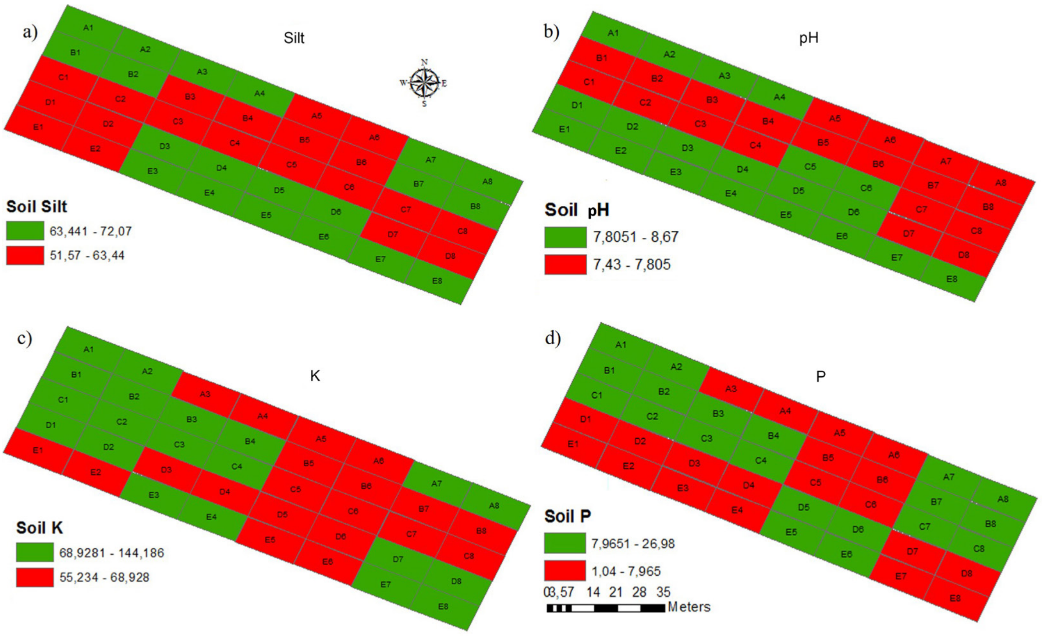

Figure 6. Soil parameters maps for silt texture, % (a); pH (b); K, ppm (c); and P, ppm (d)

be reduced without affecting yield (Basso *et al.*, 2012; Sánchez, 2015) and net return (Basso *et al.*, 2012). Specifically, Sánchez (2015) recently indicated that N is not required in large quantities (50-60 kg per season) to retain good quality and production. Furthermore, VRA technique can be considered as an environmentally friendly practice, since N losses are usually lower if the N supply does not greatly exceed crop N requirements (Schlegel *et al.*, 1996; Dobermann *et al.*, 2006).

Correlation analyses between N-VRA and yield showed that N rate was not correlated with yield of the same year for 2012 and 2013. Thus, N application did not affect the same year's yield, which indicates that N application in 2013 itself did not affect fruit set of the 2013 crop season, as it was mentioned earlier. However, N rate in 2012 positively correlated with 2013 yield (r= 0.375, p<0.001) suggesting that N availability could affect flower bud formation for the next season's bloom, fruit retention and growth. Thus, early spring

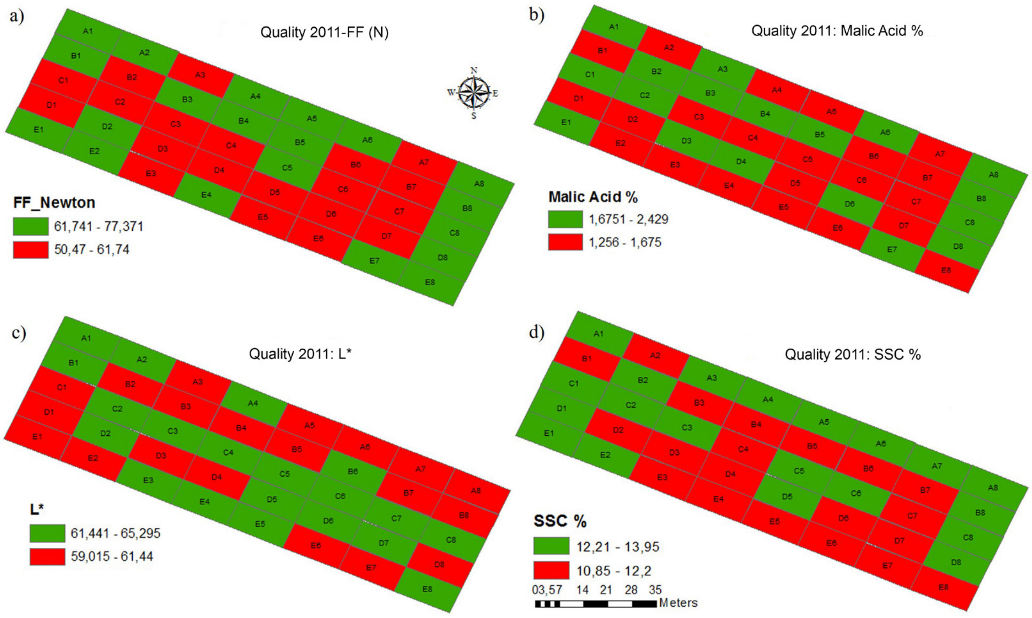

Figure 7. Yield and quality maps for 2011: FF (a), % malic acid (b), L*(c), %SSC (d)

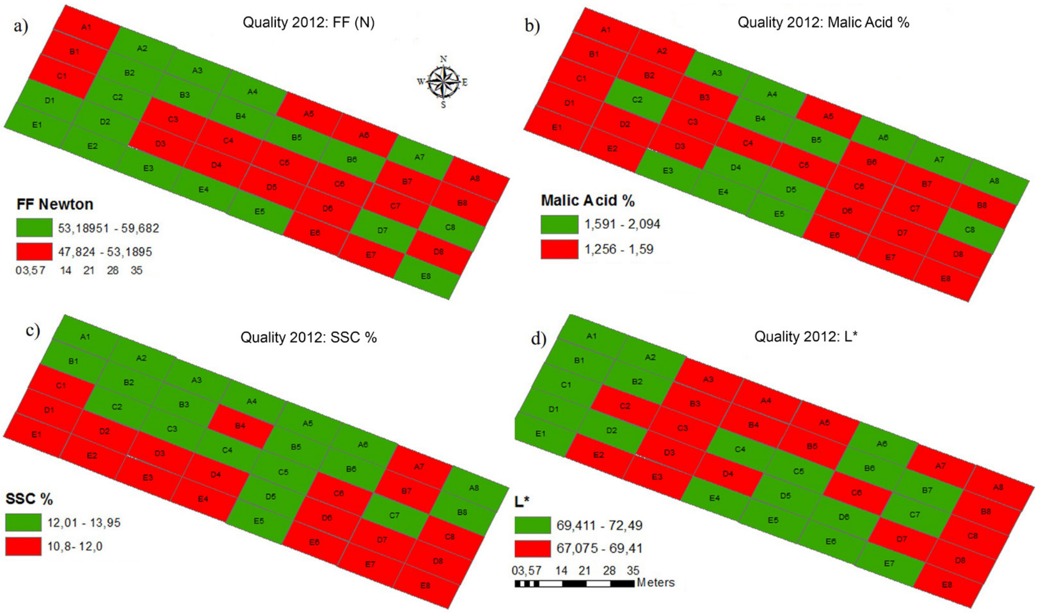

Figure 8. Quality maps for 2012: FF (a), % malic acid (b), % SSC (c), L* (d)

applied N, besides supporting vegetative growth, could play a double role by participating both in the young fruitlet growth of the same year's production and the bud formation for the following year's crop (Sanchez, 2002). Further testing of the correlation is needed so that N prescription maps of one year could be used as potential pattern of the following year's yield. Additionally, after the 2012 N-VRA the minimum yield production capacity of the trees doubled from 13.3 kg/tree in 2011 to 26 kg/tree in 2012, while the maximum fruit production remained almost the same with 44.5 kg/tree in 2011 and 50.7 kg/tree in 2012. This indicates a positive effect of VRA on NUE based on the tree's production capacity in the present year.

Following the replenishment strategy for variable rate N fertiliser, which has been initially suggested by Aggelopoulou *et al.* (2011) and Heege (2013) and implemented by Liakos *et al.* (2013) in an apple orchard, it was revealed that N-VRA can be both a profitable practice for the farmer, due to fertiliser use reduction, and an environmentally sound technique due to improved N utilization. Therefore, it should be noted

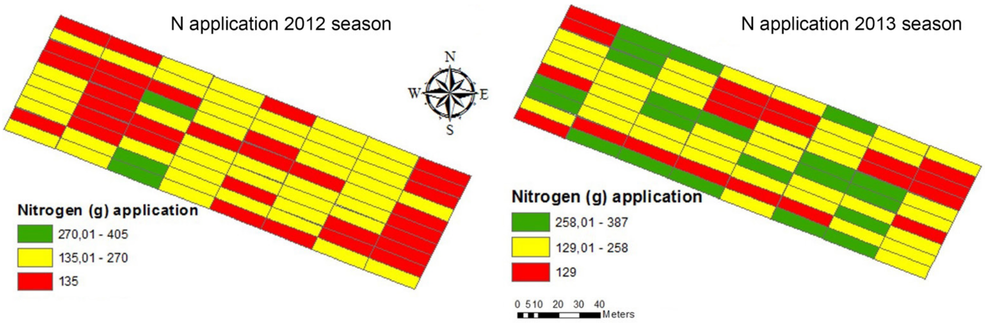

Figure 9. Nitrogen application maps for 2012 (based on the yield of 2011) and 2013 (based on the yield of 2012)

that the replenishment strategy is an easy method for small orchards to apply VRA, as it only requires a low cost GPS receiver and by weighing the mean weight of the bins to plot them in a simple GIS package.

From the results of this experiment it can be concluded that yield and soil chemical properties demonstrated spatial variability despite the small orchard size, indicating the beneficial potential use of site-specific management. This PA technique will lead to the delineation of management zones even for small fields, which is of high importance for high value crops. Also, it was revealed a tendency to have high yields correlated to lower fruit quality. Following the replenishment method (based on nutrient removal from the crop and prunings) a N site-specific fertilisation map was created and VRA technique was performed for N fertiliser application, resulting in 56% and 50% savings in 2012 and 2013, respectively, compared to homogeneous applications. It is highlighted that after the first N-VRA (2012) the low yielding areas increased the yield of the subsequent year by 51%, while there was no effect in the high yielding areas. N-VRA seems to affect the following year's yield pattern indicating the importance of N to the formation of flower buds of the following year's crop, as well as implies better utilization of N of the same year's crop.

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