

Effect of trees on the reduction of nutrient concentrations in the soils of cultivated areas

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Abstract The function of trees in reducing nutrient migration to groundwaters in cultivated areas, under Mediterranean climate conditions, is tested. Three cultivated fields were monitored for two cultivation periods. The common characteristic of the three fields was that on one side, they bordered with a poplar tree field. Four different crops were cultivated, and two cultivation periods were monitored. Based on the number of fields (i.e., three) and the cultivation periods (i.e., two), six different conditions (systems) were studied with four crops (i.e., sunflower, cotton, rapeseed, and corn). Soil samples were collected in all systems at the beginning, the middle, and the end of the cultivation period at various sampling sites (i.e., various distances from the tree row) and at various depths, and were analyzed in the laboratory for the determination of $\text{NO}_3\text{-N}$ and P-Olsen. In all systems, the greatest concentration of P-Olsen was measured in the surface layers

(0–5, 10–15, and 30–35 cm) and was gradually decreased in the deeper layers (55–60 and 75–80 cm) indicating that P mobility is low. The $\text{NO}_3\text{-N}$ concentration in the deeper layers (55–60 and 75–80 cm) at all sampling sites was equal to or greater than that of the surface layers, indicating that $\text{NO}_3\text{-N}$ has high mobility in soils. At the sampling sites in the soil zone near the tree row, the $\text{NO}_3\text{-N}$ concentration in the deeper layers was lower than that of the surface, indicating that the tree root system takes up nutrients which otherwise would move toward the water table. There was also a reduction observed of the depth-averaged P-Olsen and $\text{NO}_3\text{-N}$ concentrations at the soil zone at a distance of 2.0–3.5 m from the tree row compared to locations more distant from the trees; this reduction ranged between 15 and 50 % and 36 and 54 %, respectively. The results indicate that planting of trees in cultivated fields can contribute to the reduction of nitrate pollution of groundwaters.

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Introduction and background

The agricultural use of nutrients (e.g., nitrogen, phosphorus) in chemical and organic fertilizers has been a major source of contamination in several Mediterranean countries, e.g., Greece (Gikas et al. 2006a, b; Gemitzi et al. 2009; Boskidis et al. 2010), Italy (Saccon et al. 2013), France (Flipo et al. 2007), and Spain (Boy-Roura

et al. 2013), among others. Contaminated surface runoff or deep percolation of nutrients pose serious threats to aquatic systems and ecosystem health, possible health hazards to humans, as well as inefficient use of natural resources.

In Greece, pollution problems from agricultural activities are serious. After a continuous increase (about 75 %) in the application of fertilizers in the period 1970 to 1991, a reduction by 38 % of nitrogen and 41 % of phosphorus has been observed in the period 1991–2004 (OECD 2008; Beopoulos 1996), bringing the application rates close to the levels in the early 1970s. Particularly for nitrogen, this reduction was significant in comparison to OECD and other European Countries. The pollution problem mostly occurs as eutrophication of surface waters (Gikas 2014; Gikas et al. 2006a, b, 2009a, b; Markou et al. 2007; Boskidis et al. 2010, 2011, 2012a) and nitrate pollution of groundwaters (Mohammad and Jagath 2005; Almashri 2007; Gemitzi et al. 2009; Boskidis et al. 2012b), and is a result of (a) over-watering and over-fertilization, i.e., water and nutrients supplied in excess amounts and not to the root zone, which is the most active part of the crop and the most efficient way (Tsihrintzis et al. 1996, 1997); and (b) lack of application of best management practices (BMPs) in agriculture. Since agriculture is, and should continue being, among the main pillars of the economy of Greece, farmers need to adopt new and more sustainable practices to reduce or eliminate nutrient contamination.

BMPs are used in agriculture to address pollution problems, aiming to reduce pollutants to the maximum possible degree, and prevent them from reaching surface waters or groundwater. The hypothesis is tested in this study that the common cultivation of trees and crops can be an effective BMP to address pollution problems related to agriculture (Udawatta et al. 2002; Anderson et al. 2009; Jose 2009; Nair and Graetz 2004).

Trees in tree-crop systems may be fruit (e.g., olive, walnut, almond, etc.) or forestry (e.g., oak, poplar, chestnut, etc.) trees; crops can be herbaceous plants, such as cereals (e.g., wheat, barley, rye, oats), legumes (e.g., beans), industrial crops (e.g., corn), and fodder (e.g., alfalfa). Vine, a nonherbaceous plant, can also be cultivated in tree-crop systems, since it coexists with trees in many parts of the Mediterranean area (Papanastasis 2005). Relevant to this study, advantages of tree-crop systems, compared to single-crop systems, include the following (Sidiropoulou 2011; Papanastasis

2005; Millennium Ecosystem Assessment 2005): control of nutrient transport in the vadoze zone and storage for future soil enhancement in nutrients (Tully et al. 2012), enhancement of water quality (Jose 2009; Tyndall and Colletti 2007; Nair et al. 2007; Allen et al. 2004; Udawatta et al. 2010; Friend et al. 2006; Anbumozhi et al. 2005; Ridolfi et al. 2003), runoff volume and peak reduction, allowing for additional water percolation to the subsoil (Anderson et al. 2009), and reduction of soil salinization (Ellis et al. 2005).

This study tests the function of trees in reducing nutrient transport to groundwaters in cultivated areas, under Mediterranean climate conditions. The hypothesis tested is that the deep roots of trees create a protecting net underneath the root system of the crop, which uptakes excess nutrients (i.e., those quantities of the applied fertilizers leaching under the crop roots), and blocks them from moving into the vadoze zone (particularly nitrates) and reaching the groundwater table. This hypothesis has not been tested yet under Mediterranean climate conditions.

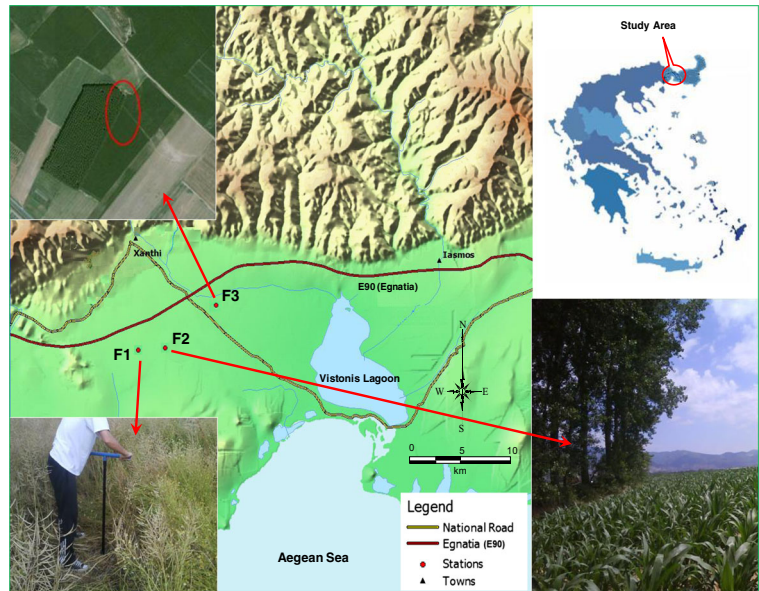
To test the validity of this hypothesis, monitoring was undertaken in real cultivation conditions in three agricultural fields during 2010, 2011 and 2012 growing seasons. During the monitoring, we collected samples and made analyses of nutrient concentrations and other parameters in soils, where common intercropped cultivations of trees (poplar) and crops (sunflower, rapeseed, cotton, and corn) existed. This was done by collecting soil samples at various distances from the trees and at various depths down to 0.8 m in the soil profile. The collected samples were analyzed in the laboratory using standard methods for physicochemical parameters (i.e., pH, nitrate-nitrogen, and phosphorus) to demonstrate the protective effect of the trees on nutrient transport reduction to groundwater.

Materials and methods

Study area

From years 2010 to 2012, the study took place in three cultivated fields (F1, F2, F3) in Xanthi plain in North-eastern Greece. Figure 1 presents general location map where the three experimental fields F1, F2 and F3 (red dots) are located. The common characteristic of the three fields is that on one side they border with a poplar (*Populus* L.) tree field. The poplar trees were about

Fig. 1 Location map and photographs of the three experimental fields F1, F2, and F3



20 years old in F1 and F2 fields and about 30 years old in F3 field. The distance between the poplar trees was 7 m; however, this distance between trees is not a parameter affecting the results since the data were collected at various sampling stations along one line starting from one tree and directed perpendicularly to the tree row, as shown in Fig. 2. The effect of the poplar trees on the transport of nutrients in the soil profile of the cultivated fields was tested.

Table 1 presents the cultivation period, the crops, and the fertilizer quantity applied on the three fields F1, F2

and F3. Sunflower (*Helianthus annuus* L.) (F1-S system) was cultivated in the first field (F1) during the cultivation period 2010 (i.e., April to September) and rapeseed (*Brassica napus* L.) (F1-R system) was also cultivated in the first field F1 during the cultivation period 2010–2011 (i.e., October to June) (Table 1). Cotton (*Gossypium hirsutum* L.) (F2-Ct system) was cultivated in the second field (F2) during the cultivation period 2010 and corn (*Zea mays* L.) (F2-Cr system) was also cultivated in the second field (F2) during cultivation period 2011 (both from April to October) (Table 1). Finally, corn was

Table 1 Crops and fertilizer application in the three fields F1, F2, and F3

Field	Crop	System	Cultivation period	Fertilizer application		
				Date	Type (N-P-K) ^a	Quantity (kg ha ⁻¹)
F1	Sunflower (S)	F1-S	April–September 2010	2 April 2010	21-7-14	250
				25 May 2010	33.5-0-0	200
	Rapeseed (R)	F1-R	October 2010–June 2011	5 October 2010	29-6-15	200
F2	Cotton (Ct)	F2-Ct	April–October 2010	10 March 2011	25-0-0	200
				10 April 2010	20-10-20	250
	Corn (Cr)	F2-Cr	April–October 2011	5 June 2010	26-0-0	200
F3	Corn (C1)	F3-C1	April–October 2011	30 March 2011	24-6-12	600
				27 May 2011	40-0-0	500
	Corn (C2)	F3-C2	April–October 2012	28 March 2011	22-11-0	750
				25 May 2011	25-0-0	400
				30 March 2012	20-10-10	700
				20 May 2012	26-0-0	400

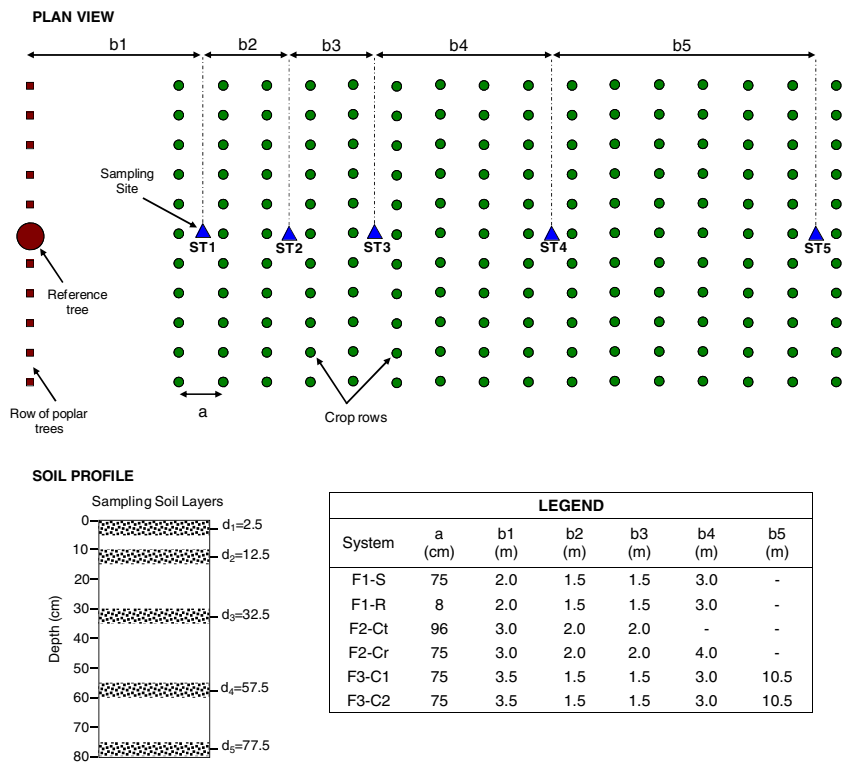
^a N nitrogen, P phosphorus, K potassium

cultivated in the third field (F3) from April to October during the two cultivation periods, 2011 (F3-C1 system) and 2012 (F3-C2 system) (Table 1). Each field was monitored for two cultivation periods with different (e.g., fields F1 and F2) or same (field F3) crops; as a result, six experimental tree-crop systems were studied (Table 1). Crops cultivated in field F1, in the previous years, were corn and wheat in 2008 and 2009, respectively, while in fields F2 and F3, corn was cultivated both in 2008 and 2009 cultivation periods.

Figure 2 is general, presenting all experimental plots. It presents the experimental field, with the tree row and the planted crops, the distances between crops and the sampling sites, and the sampling layers for each case. The sunflower and the corn were sowed in rows at a distance of 75 cm by plowing method. The rapeseed and the cotton were sowed in rows at distances of 8 and 96 cm, respectively (Fig. 2). The distances between planted crops were different depending on crop characteristics (i.e., size, irrigation, harvesting method, and equipment). For all crops, 1 or 2 days before sowing, basic fertilizer was applied on the field and about 2 months after sowing surface fertilizer was applied, at quantities presented in

Table 1. The total amount of nutrients applied during the cultivation period on F1-S, F1-R, F2-Ct, F2-Cr, F3-C1, and F3-C2 systems were 119.5, 108.0, 102.0, 344.0, 265.0, and 244.0 kg ha⁻¹, respectively, for nitrogen, and 7.6, 5.2, 10.9, 15.7, 36.0, and 30.5 kg ha⁻¹, respectively, for phosphorus. The fertilizer was embodied to the surface soil layers at depths of 10 cm for the initial fertilizers and at depths of 5 cm for the surface fertilizers. The plots were irrigated following crop needs based on ET computation by FAO 56. The “traveling gun” was the method of irrigation used at the three experimental fields. This is a sprinkler irrigation system consisting of a single large nozzle that operates under pressure, rotates, and is self-propelled. The main parameters used to describe effects of irrigation water on crop production are as follows: pH, electrical conductivity, and sodium adsorption ratio (SAR). The quality of irrigation water was considered suitable for the crops used (i.e., cotton, rapeseed, sunflower, and corn), as the pH value ranged between 6.6 and 7.8, the electrical conductivity was lower than 1.5 mS/cm and SAR value ranged between 0.6 and 2.8 (Bauder et al. 2011; Gikas et al. 2013).

Fig. 2 Schematic general layout of the sampling locations of soil material in the three experimental fields and vertical soil layer sampling horizons. (ST_{*i*} = sampling station; *a* = distance (m) between crop rows; *b_i* = distance (m) between sampling stations; *d_i* = depth (cm) of sampling layers from soil surface)



Sampling and soil analyses

Before sowing

Soil samples were taken in all fields before sowing at various depths (i.e., 0–5, 10–15, 30–35, and 55–60 cm) and analyzed for texture, i.e., percent clay, silt, and sand content, by the Bouyoucos method (Pansu and Gautheyrou 2006). The soil samples were also analyzed to determine pH and the concentration of organic matter, and available trace metal elements (i.e., Fe, Zn, Mn, Cu). The metals were determined by flame atomic absorption spectroscopy (FAAS) according to methods of soil analysis (SSSA Book Series 1996).

After sowing

Soil samples were collected in all systems at the beginning (i.e., after sowing), the middle, and the end of the cultivation period. Specifically, three sampling surveys took place in F1-S (sampling 1: 5 May 2010; sampling 2: 3 July 2010; sampling 3: 2 September 2010), F1-R (sampling 1: 7 November 2010; sampling 2: 14 April 2011; sampling 3: 10 June 2011), and F2-Ct (sampling 1: 5 May 2010; sampling 2: 3 July 2010; sampling 3: 7 October 2010) systems, and four sampling surveys in F2-Cr (sampling 1: 14 April 2011; sampling 2: 10 June 2011; sampling 3: 20 July 2011; sampling 4: 13 September 2011), F3-C1 (sampling 1: 14 April 2011; sampling 2: 10 June 2011; sampling 3: 20 July 2011; sampling 4: 13 September 2011), and F3-C2 (sampling 1: 6 April 2012; sampling 2: 14 May 2012; sampling 3: 24 July 2012; sampling 4: 28 September 2012) systems. The samples were collected at various depths, i.e., 0–5, 10–15, 30–35, 55–60, and 75–80 cm, and at various distances from the poplar trees (i.e., sampling sites), as shown in Fig. 2. In the sunflower-poplar tree system (F1-S) and in the rapeseed-poplar tree system (F1-R), the distances from the poplar tree row were 2.0, 3.5, 5.0, and 8.0 m. In the cotton poplar tree system (F2-Ct), the distances from the poplar tree row were 3.0, 5.0, and 7.0 m, and in the corn-poplar tree system (F2-Cr), the distances were 3.0, 5.0, 7.0, and 11.0 m. Finally, in the corn-poplar tree systems (F3-C1 and F3-C2), the distances from the poplar tree were 3.5, 5.0, 6.5, 9.5, and 20 m (Fig. 2).

Soil samples were air-dried immediately after collection, and then analyzed (in duplicate) in the laboratory for the determination of pH, nitrate nitrogen (NO₃-N),

and phosphorus Olsen (P-Olsen). Soil pH was determined on 1:2 soil/water ratio. NO₃-N was determined by a spectrophotometric method using copper sulfate solution 0.02 N for extraction (Ryan et al. 2001). P-Olsen was determined by extracting the soil with 0.5 M NaHCO₃ and determining P on the filtrate collected after passing through a 0.45-μm filter (Pierzynski 2000). Phosphorus in solution was determined by the stannous chloride method (APHA, AWWA 1998). The concentrations of NO₃-N and P-Olsen are expressed in micrograms per gram dry soil (μg/g).

Statistical analyses

Statistical analysis was performed to see if there were statistical significant differences between measured P-Olsen and nitrate nitrogen (NO₃-N) concentrations at the various sampling sites (i.e., distances from the tree row) in each system. For this purpose, one-way ANOVA was used at 95 % confidence interval ($p < 0.05$) for each system separately. Where the ANOVA showed significant differences between stations ($p < 0.05$), the Tukey honestly significant difference (HSD) test was used to identify between which stations there was statistical significant difference. Data normality was checked with the Shapiro-Wilk test. All analyses were done using SPSS 15.0 for windows software package.

Calculation of the depth-averaged nutrient concentration

At each field (i.e., system) and at each sampling site of the experimental tree-crop systems, we calculated the depth-averaged concentrations (DACs) of nitrate nitrogen (NO₃-N) and P-Olsen, for all cultivation periods. As mentioned before, the sampling depths were at 0–5 (surface), 10–15, 30–35, 55–60, and 75–80 cm, corresponding to mean depths of 2.5, 12.5, 32.5, 57.5, and 77.5 cm, respectively; because the sampling depths were not equally spaced, for finding a depth-averaged concentration at each sampling station, the following Eq. (1) was used:

$$DAC = \frac{2.5c_1 + \sum_{i=1}^{n-1} \frac{c_i + c_{i+1}}{2} (d_{i+1} - d_i)}{d_n} \tag{1}$$

Table 2 Soil texture and physicochemical parameters of the three fields at the beginning of the experiment

Field	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Soil texture ^a	Organic Matter (%)	pH	Fe (ppm)	Zn (ppm)	Mn (ppm)	Cu (ppm)
F1	0–5	11.1	11.8	77.1	Sandy loam	0.77	7.4	13.04	0.68	4.63	0.35
	10–15	12.0	10.6	77.4	Sandy loam	1.04	7.2	18.13	1.15	4.90	0.37
	30–35	9.5	15.5	75.0	Sandy loam	0.60	7.2	21.96	0.53	5.00	0.47
	55–60	14.2	23.8	62.0	Sandy loam	0.43	7.3	32.10	0.58	8.01	0.78
F2	0–5	10.4	23.3	66.3	Sandy loam	1.05	7.8	11.01	2.25	3.86	1.40
	10–15	10.7	21.2	68.1	Sandy loam	0.87	7.8	9.74	2.40	3.78	1.39
	30–35	10.0	19.5	70.5	Sandy loam	0.41	7.7	12.09	1.91	3.00	1.22
	55–60	15.9	21.4	62.7	Sandy loam	0.46	7.8	17.89	1.61	3.52	1.90
F3	0–5	6.4	25.6	68.0	Sandy loam	1.10	6.9	19.55	1.62	6.47	1.65
	10–15	6.4	25.6	68.0	Sandy loam	0.91	7.1	26.17	1.59	7.93	1.88
	30–35	5.9	29.9	64.2	Sandy loam	0.66	7.1	19.59	1.35	5.92	1.63
	55–60	4.6	29.6	65.8	Sandy loam	0.55	7.2	16.88	0.48	5.32	1.48

^a Based on USDA Soil Conservation Service texture triangle

where DAC is the depth-averaged concentration ($\mu\text{g/g}$); c_i is the concentration ($\mu\text{g/g}$) of nutrient (N or P) at sampling depth i ; d_i is the mean depth (cm) of sampling soil layer (i.e., $d_1=2.5$ cm, $d_2=12.5$ cm, etc.; Fig. 2); n is the number of sampling soil layers; and d_n is the total sampling depth (cm). The values of index i are 1, 2, 3, etc., corresponding to the first, second, third (i.e., 0–5, 10–15, 30–35 cm) etc. soil sampling layers.

Results

Monitoring and statistical analysis results

The results of soil texture, organic matter concentration, pH values, and concentration of micronutrient cations (Fe, Zn, Mn, Cu) at the beginning of the experiment in three fields are presented in Table 2. The soil texture of the three fields is sandy loam (Table 2). The organic matter in fields F1, F2, and F3 was measured and found to range from 0.43 to 1.04 %, 0.41 to 1.05 %, and 0.55 to 1.10 %, respectively (Table 2).

Measured pH values in the six systems ranged between 6.9 and 7.7 for the F1-S system, 6.4 and 7.9 for the F1-R system, 7.5 and 8.0 for F2-Ct system, 7.4 and 8.2 for F2-Cr system, 5.6 and 7.7 for F3-C1 system, and 5.6 and 7.1 for F3-C2 system. The mean values of all pH values for each of the six systems, i.e., F1-S, F1-R, F2-Ct, F2-Cr, F3-C1, and F3-C2 were 7.3, 7.3, 7.8, 7.8, 6.9, and 6.6, respectively. Values did not differ when measured in the same field and at different seasons. Small differences

in pH values between fields are due to the small variation of the chemical composition of soils. However, all pH values are typical of the soils in the major study area.

Figure 3 presents P-Olsen and $\text{NO}_3\text{-N}$ concentrations at each sampling location (Fig. 2) for all sampling campaigns in F1-S and F1-R systems. Sometimes we could not take a soil sample at a certain depth (e.g., at the depth of 55–60 cm and at the depth of 75–80 cm of the F1-S system; Fig. 3a), particularly when the soil was dry and/or rocks would not allow our auger to fully penetrate the soil. At the first (0–5 cm) and second (10–15 cm) soil layers of the F1-S system, the P-Olsen concentration was greater at the beginning of the cultivation period (sampling 1) at most locations and ranged between 29.9 and 39.2 $\mu\text{g/g}$ and 22.1 and 28.7 $\mu\text{g/g}$, respectively (Fig. 3a). At the depth of 30–35 cm, the P-Olsen concentration at the beginning, the middle, and the end of the cultivation period ranged between 14.0 and 19.9 $\mu\text{g/g}$, 10.5 and 21.6 $\mu\text{g/g}$, and 7.6 and 8.1 $\mu\text{g/g}$, respectively, and was lower than that at the surface soil layers; this reduction is due to phosphorus uptaking by the crops. Also, at the same depth (30–35 cm), the P-Olsen concentration was lower at location F1-S-ST1 (distant 2 m from the trees) and increased at greater distances from the trees (i.e., 3.5,

Fig. 3 P-Olsen concentration in **a** F1-S system and **b** F1-R system; $\text{NO}_3\text{-N}$ concentration in **c** F1-S system and **d** F1-R system (experimental field F1; S = sunflower, April–September 2010, sampling 1: 5 May 2010, sampling 2: 3 July 2010, sampling 3: 2 September 2010; R = rapeseed, October 2010–June 2011, sampling 1: 7 November 2010, sampling 2: 14 April 2011, sampling 3: 10 June 2011)

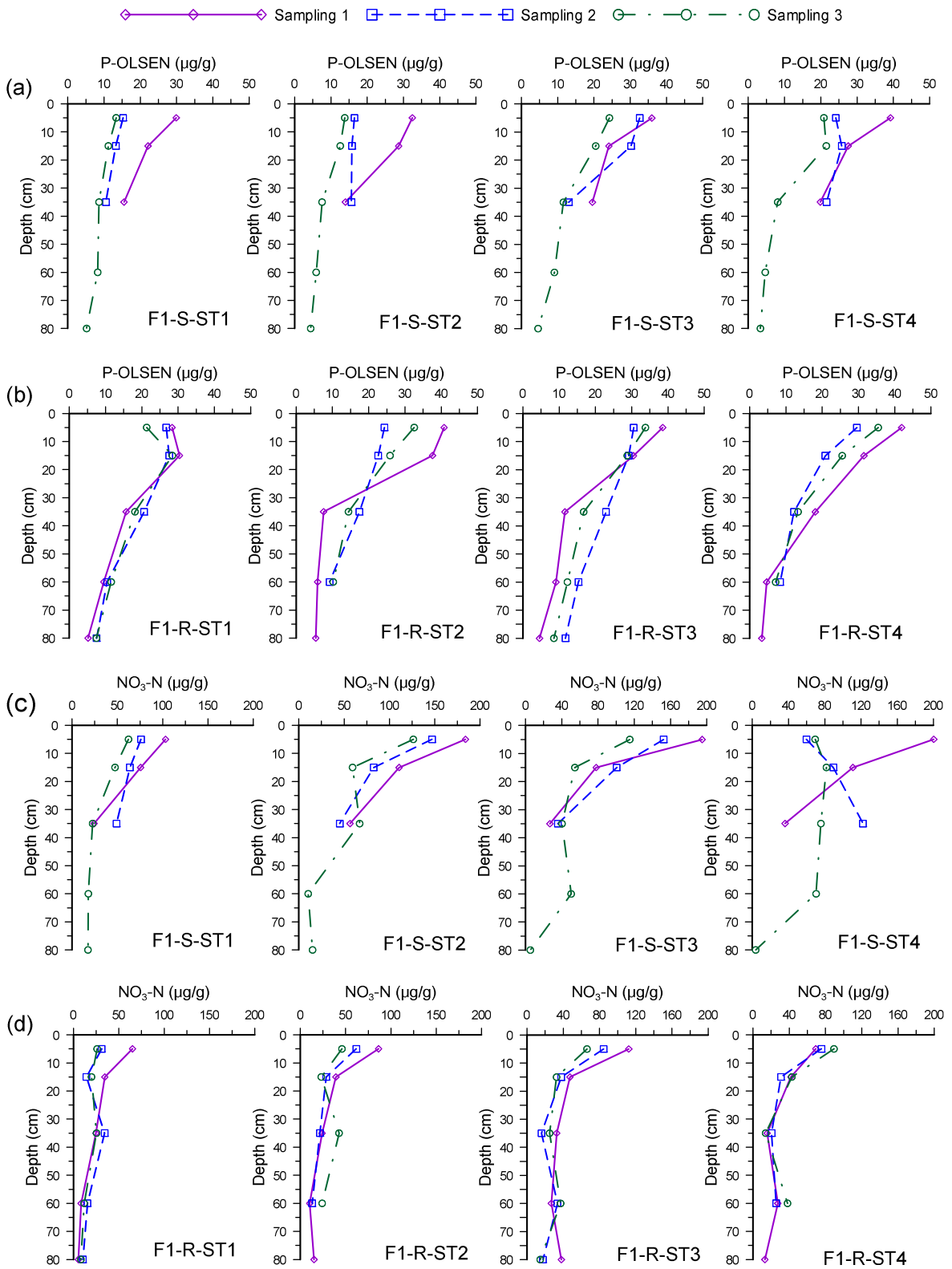


Table 3 One-way ANOVA results for sampling sites of the six experimental tree-crop systems (the ANOVA was performed for each system separately)

System	Parameter	One-way ANOVA		Tukey HSD		
		<i>F</i>	<i>p</i>	Site (I)–site (J)	Mean Difference (I–J)	<i>p</i>
F1-S	P-Olsen	1.372	0.265	–	–	–
	NO ₃ -N	1.069	0.373	–	–	–
F1-R	P-Olsen	0.095	0.962	–	–	–
	NO ₃ -N	3.357	0.026	ST1–ST3	–21.38	0.029*
F2-Ct	P-Olsen	4.793	0.017	ST1–ST4	–19.71	0.045*
				ST1–ST2	–9.39	0.046*
F2-Cr	P-Olsen	5.008	0.003	ST1–ST3	–10.53	0.023*
				ST1–ST4	–46.01	0.048*
F3-C1	P-Olsen	2.832	0.029	ST1–ST4	–8.88	0.002*
				ST1–ST5	–37.17	0.032*
F3-C2	P-Olsen	8.271	0.001	ST1–ST3	–7.57	0.031*
				ST1–ST4	–6.93	0.048*
F3-C2	NO ₃ -N	5.462	0.001	ST1–ST5	–59.09	0.004*
				ST1–ST4	–76.02	0.001*
F3-C2	NO ₃ -N	5.462	0.001	ST1–ST5	–73.54	0.001*
				ST1–ST3	–9.54	0.012*
F3-C2	NO ₃ -N	5.462	0.001	ST1–ST4	–14.21	0.001*
				ST1–ST5	–13.56	0.001*
F3-C2	NO ₃ -N	5.462	0.001	ST1–ST3	–44.96	0.005*
				ST1–ST4	–47.90	0.003*
F3-C2	NO ₃ -N	5.462	0.001	ST1–ST5	–51.81	0.001*

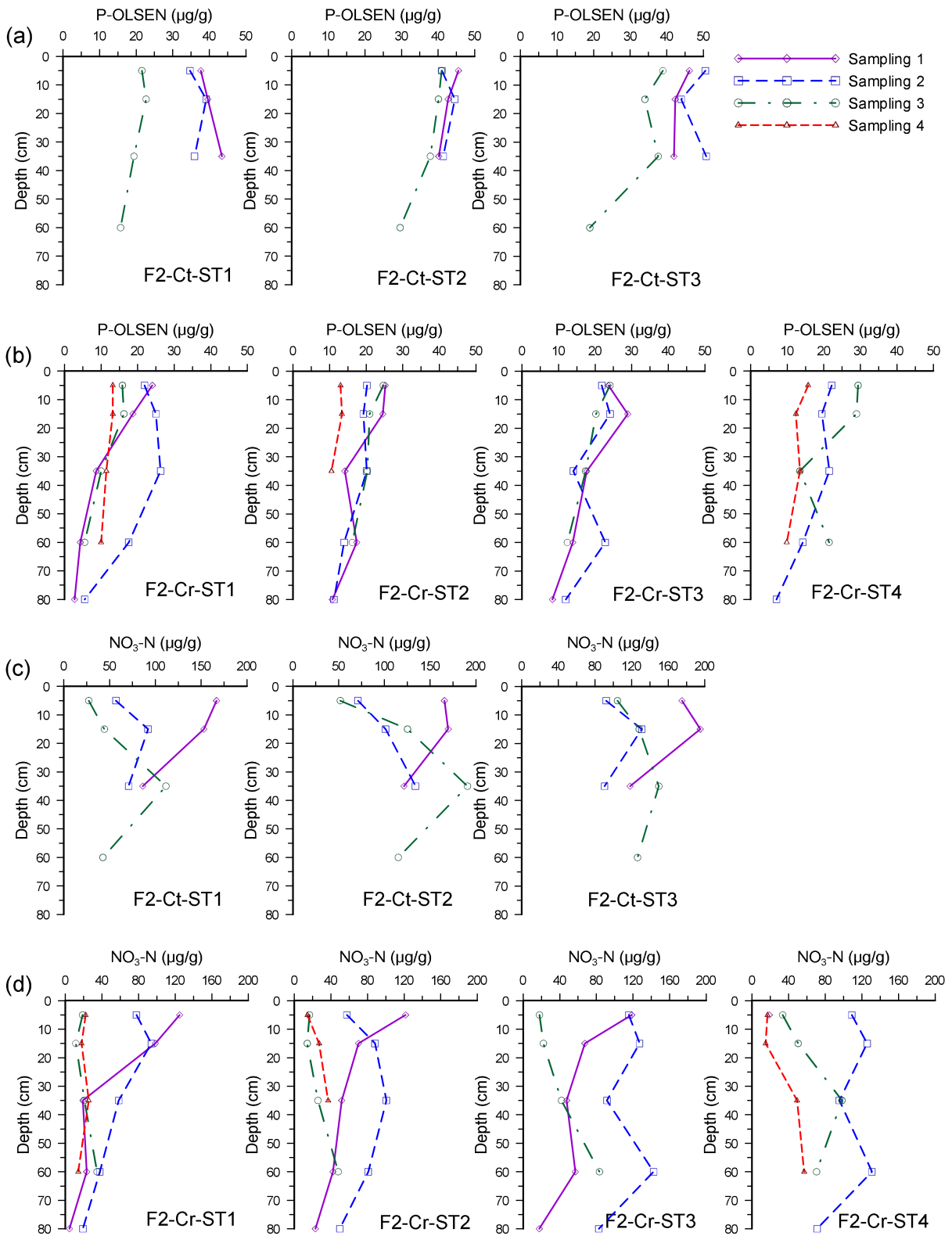
*The mean difference is significant at the 0.05 level

5, and 8 m; Figs. 2 and 3a); this is attributed to the action of the root system of poplar trees, which uptake nutrient quantities; as a result, the concentration is greater at greater distances from the poplar trees. At the deeper soil layers, the P-Olsen concentration was reduced at all sampling locations and reached the level of 10 µg/g at the depth of 55–60 cm, and 5 µg/g at the depth of 75–80 cm, indicating that phosphorus mobility to the deeper layers is limited (Fig. 3a). The one-way ANOVA between groups showed that there is not statistically significant difference between sampling sites (i.e., distances from the tree row) for P-Olsen (Table 3).

P-Olsen concentration in the soil profile of the F1-R system follows a similar pattern with that of the F1-S system (Fig. 3b). At the surface soil layers (i.e., 0–5 and 10–15 cm) at the F1-R-ST1, F1-R-ST2, F1-R-ST3, and F1-R-ST4 sampling sites, the P-Olsen concentration ranged between 21.3 and 28.4 µg/g, 22.6 and 40.8 µg/g, 28.8 and 33.8 µg/g, and 20.8 and 41.9 µg/g,

respectively; at the deeper soil layers, there was a gradual reduction of phosphorus concentration at all sampling locations (Fig. 3b). The P-Olsen concentrations at F1-R-ST1 site (distant 2 m from the trees) of the F1-R system were higher than that at F1-S-ST1 of the F1-S system (Fig. 2a, b); this is probably due to the fact that the rapeseed is a winter crop (cultivated from October to June) when the poplar trees are not active (from November to March), and consequently, the uptake of phosphorus by the root system of poplar trees is limited. The one-way ANOVA between groups showed that

Fig. 4 P-Olsen concentration in **a** F2-Ct system and **b** F2-Cr system; NO₃-N concentration in **c** F2-Ct system and **d** F2-Cr system (experimental field F2; Ct = cotton, April–October 2010, sampling 1: 5 May 2010; sampling 2: 3 July 2010; sampling 3: 7 October 2010; Cr = corn, April–October 2011, sampling 1: 14 April 2011; sampling 2: 10 June 2011; sampling 3: 20 July 2011; sampling 4: 13 September 2011)



there is no statistically significant difference between sampling sites for P-Olsen (Table 3).

Figure 3c presents the $\text{NO}_3\text{-N}$ concentrations at each sampling location and at different depths, measured during the four field campaigns, in the F1-S system. At the surface layers (0–5 and 10–15 cm), the $\text{NO}_3\text{-N}$ concentration was greater at the beginning of the cultivation period (it ranged between 75.6 and 200.3 $\mu\text{g/g}$), due to the first fertilization (Table 1), and showed a gradual decrease with time; and at the end of the cultivation period, it ranged between 47.5 and 126.3 $\mu\text{g/g}$ (Fig. 3c). At a depth of 30–35 cm, the lowest $\text{NO}_3\text{-N}$ concentration was measured at the end of the cultivation period (location F1-S-ST1, 22.7 $\mu\text{g/g}$). At depth of 55–60 cm, at location F1-S-ST3, the $\text{NO}_3\text{-N}$ concentration was greater than that at depth of 30–35 cm, and at locations F1-S-ST1 and F1-S-ST4, the $\text{NO}_3\text{-N}$ concentrations were comparable to those at 30–35 cm, indicating greater mobility to the deeper soil layers, as nitrate dissolves in the rain and/or irrigation water. At the same depth (55–60 cm), at locations F1-S-ST1 and F1-S-ST2, $\text{NO}_3\text{-N}$ concentrations were lower than those of F1-S-ST3 and F1-S-ST4 (Fig. 3c), indicating nitrogen uptake by the trees, given that F1-S-ST1 and F1-S-ST2 are located at 2.0 and 3.5 m from the poplar trees, respectively, and F1-S-ST3 and F1-S-ST4 are located at 5.0 and 8.0 m from the tree row. At depths 75–80 cm, at all locations, the $\text{NO}_3\text{-N}$ concentrations did not exceed 17.5 $\mu\text{g/g}$. The one-way ANOVA between groups showed that there is not statistically significant difference between sampling sites for $\text{NO}_3\text{-N}$ (Table 3).

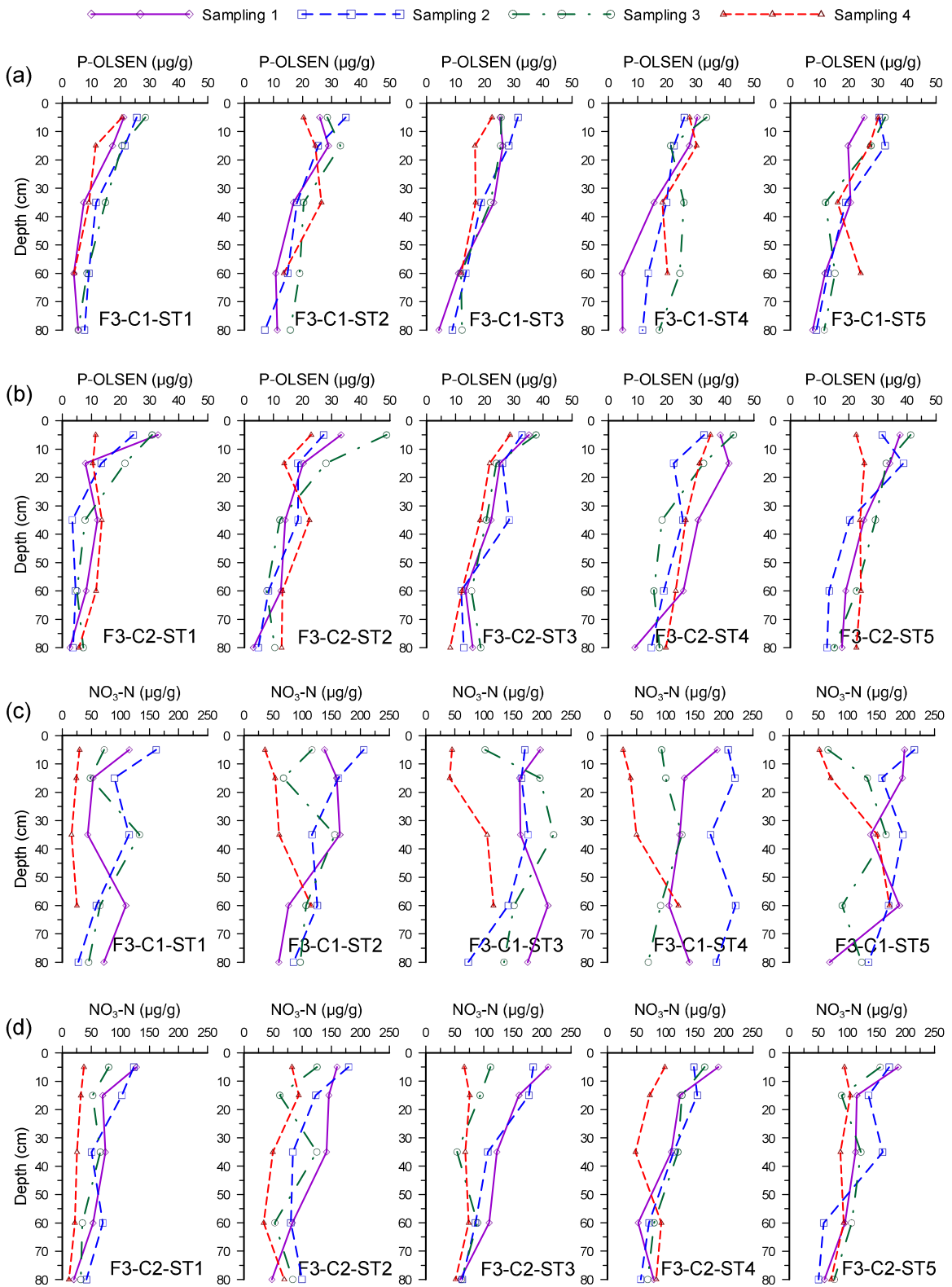
Figure 3d presents the $\text{NO}_3\text{-N}$ concentrations at each sampling location and at different depths in the F1-R system. At the surface layers (0–5 and 10–15 cm), the $\text{NO}_3\text{-N}$ concentration was greater at the beginning (sampling 1) of the cultivation period (it ranged between 34.5 and 115.3 $\mu\text{g/g}$) and was lower than the corresponding concentration in the F1-S system; this is due to the lower amount of nitrogen applied as fertilizer in the F1-R system in comparison to the F1-S (Table 1). At the end of the cultivation period and at depths 55–60 cm, the $\text{NO}_3\text{-N}$ concentration increased with distance from the poplar tree row (Fig. 3d), indicating the effect of the root system of the trees on nitrogen binding. According to the one-way ANOVA between groups, there is statistically significant difference of $\text{NO}_3\text{-N}$ between sampling sites. Post hoc comparison using the Tukey HSD test indicated that the $\text{NO}_3\text{-N}$ concentration at F1-R-ST1 (2 m from the poplar tree) was significantly lower than

that at F1-R-ST3 and F1-R-ST4 (5.0 and 8.0 m, respectively, from the poplar tree) sampling sites (Table 3). These results indicate nitrogen uptake by the root system of the trees.

In the F2-Ct system (Fig. 4a), there are no noticeable differences in P-Olsen concentrations at depths 0–5, 10–15, and 30–35 cm between the first and second sampling campaigns. At the end of the cultivation period (sampling 3: 7 October 2010), P-Olsen concentrations were lower at all locations and at all depths. At location F2-Ct-ST1 (3 m distance from the poplar tree row), the P-Olsen concentration ranged between 15.7 and 21.6 $\mu\text{g/g}$, and increased at greater distances (F2-Ct-ST2, 29.6–40.9 $\mu\text{g/g}$; F2-Ct-ST3, 19.0–38.9 $\mu\text{g/g}$). Lower concentrations of phosphorus were measured at depths 75–80 cm (Fig. 4a), indicating the low mobility of phosphorus. There is statistically significant difference of P-Olsen concentration between sampling sites (ANOVA: $F=4.793$, $p=0.017$; Table 3), and post hoc comparison using the Tukey HSD test showed that the phosphorus concentration at F2-Ct-ST2 (5 m from the tree row) and F2-Ct-ST3 (7 m from the tree row) sampling locations were significantly greater than that at F2-Ct-ST1 location (Table 3).

Figure 4b presents the P-Olsen concentrations at each sampling location and at different depths in the F2-Cr system (corn and poplar tree). At the surface soil layers (i.e., 0–5 and 10–15 cm), at the F2-Cr-ST1, F2-Cr-ST2, F2-Cr-ST3, and F2-Cr-ST4 sampling sites, the P-Olsen concentration ranged between 13.2 and 24.9 $\mu\text{g/g}$, 12.9 and 25.2 $\mu\text{g/g}$, 20.9 and 28.2 $\mu\text{g/g}$, and 12.3 and 29.37 $\mu\text{g/g}$, respectively, indicating that there were no noticeable differences between sampling locations. At the deeper soil layers, the P-Olsen concentration was reduced at all sampling locations and reached at the depth of 75–80 cm the level of 2.8 to 11.9 $\mu\text{g/g}$; this is mainly due to the low phosphorus mobility (Fig. 4b). The one-way ANOVA between groups and Tukey HSD test showed that there is statistically significant difference between stations, and the phosphorus concentration at F2-Cr-ST1 (3.0 m from the poplar tree) was significantly lower than that at F2-Cr-ST4 (11.0 m from the poplar tree).

Fig. 5 P-Olsen concentration in **a** F3-C1 system and **b** F3-C2 system; $\text{NO}_3\text{-N}$ concentration in **c** F3-C1 system and **d** F3-C2 system (experimental field F3; C1 = corn, April–October 2010, sampling 1: 14 April 2011; sampling 2: 10 June 2011; sampling 3: 20 July 2011; sampling 4: 13 September 2011; C2 = corn, April–October 2011, sampling 1: 6 April 2012; sampling 2: 14 May 2012; sampling 3: 24 July 2012; sampling 4: 28 September 2012)



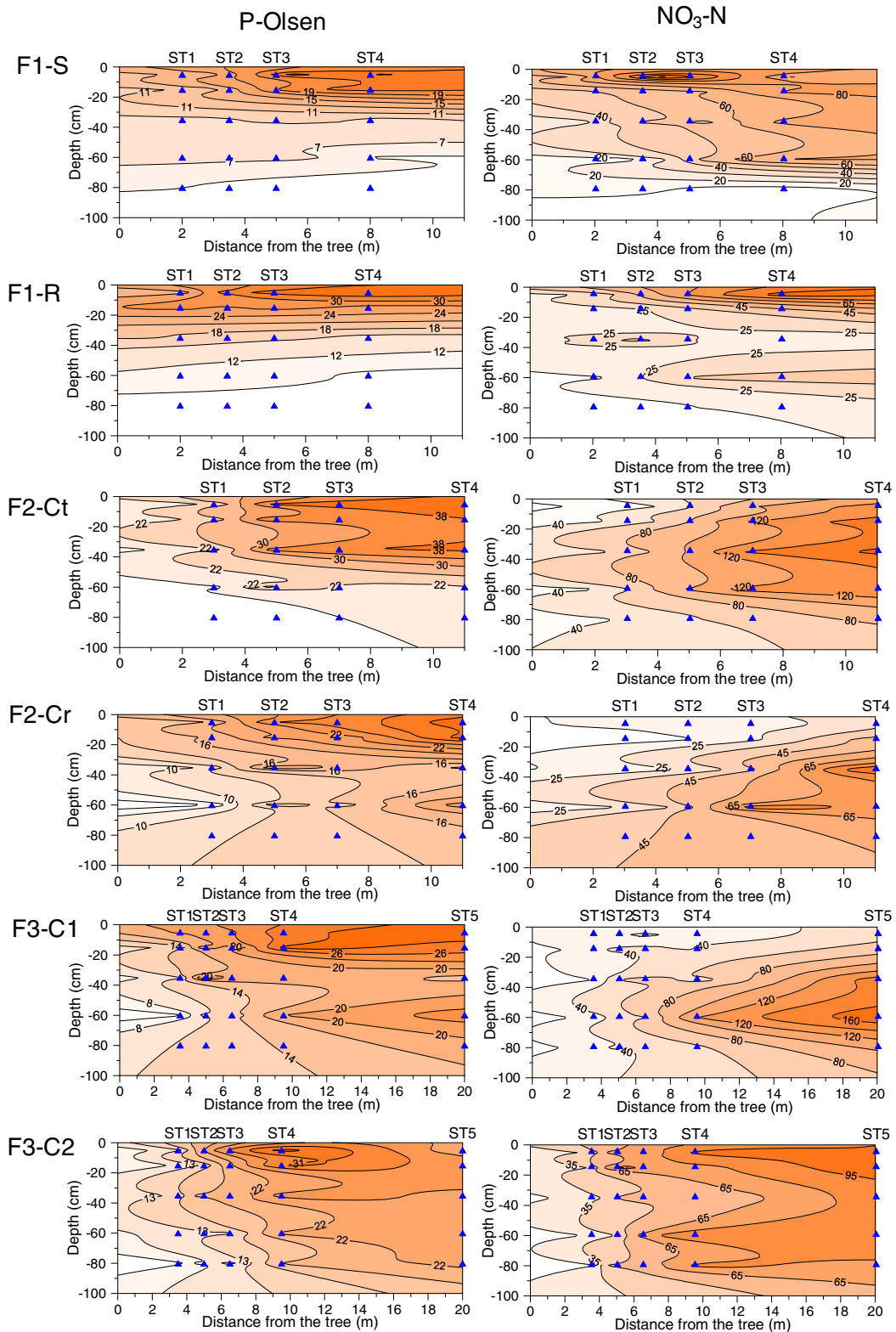


Fig. 6 Iso-concentration contours of P-Olsen and NO₃-N in a vertical soil section for the sampling survey at the end of the cultivation period in the six experimental systems. The *triangles* show the sampling sites (F1, F2, F3 experimental fields, S sunflower, R rapeseed, Ct cotton, Cr com, C1 com, C2 com)

At the surface layers (0–5 and 10–15 cm) of the F2-Ct system, the $\text{NO}_3\text{-N}$ concentration was greater at the beginning of the cultivation period (it ranged between 153.0 and 195.0 $\mu\text{g/g}$) and showed a gradual decrease with time, and at the end of the cultivation period (sampling 3), it ranged between 27.2 and 128.3 $\mu\text{g/g}$ (Fig. 4c). At the end of the cultivation period and at depths 55–60 cm, the $\text{NO}_3\text{-N}$ concentration increased with distance from the poplar tree row (Fig. 4c). According to the one-way ANOVA between groups, there is statistically significant difference of $\text{NO}_3\text{-N}$ between sampling sites. Post hoc comparison using the Tukey HSD test indicated that the $\text{NO}_3\text{-N}$ concentration at F2-Ct-ST1 (3 m from the poplar trees) was significantly lower than that at F2-Ct-ST3 (7.0 m from the poplar trees) sampling site (Table 3). Similar results to the F2-Ct system were observed in the F2-Cr system, where at the end of the cultivation period and at depths 55–60 cm, the $\text{NO}_3\text{-N}$ concentration increased with distance from the poplar tree row (Fig. 4d). At the end of the cultivation period (sampling 4) at the F2-Cr-ST1, F2-Cr-ST2, and F2-Cr-ST4 sampling sites, the $\text{NO}_3\text{-N}$ concentration ranged between 14.1 and 25.5 $\mu\text{g/g}$, 14.5 and 36.9 $\mu\text{g/g}$, and 14.8 and 57.0 $\mu\text{g/g}$, respectively; the smaller concentrations indicate greater reduction closer to the trees and is attributed to nitrogen uptake by the root system of the trees. The one-way ANOVA between groups and the Tukey HSD test showed that there is statistically significant difference between stations, and the $\text{NO}_3\text{-N}$ concentration at F2-Cr-ST1 (3.0 m from the poplar trees) was significantly lower than that at F2-Cr-ST4 (11.0 m from the poplar trees).

Figure 5 presents P-Olsen and $\text{NO}_3\text{-N}$ concentrations at each monitoring site for all sampling campaigns in F3-C1 and F3-C2 systems. At the surface soil layers (0–5 and 10–15 cm) at all sampling locations of the F3-C1 and F3-C2 systems, the P-Olsen concentration ranged between 11.5 and 34.8 $\mu\text{g/g}$ and 7.9 and 48.8 $\mu\text{g/g}$, respectively (Fig. 5a,b). At the deeper soil layers (30–35 and 55–60 cm), the mean P-Olsen concentrations at F3-C1-ST1, F3-C1-ST2, F3-C1-ST3, F3-C1-ST4, and F3-C1-ST4 sampling locations were 8.6, 17.5, 16.13, 17.9, and 16.5 $\mu\text{g/g}$, respectively. Similar results were measured at the F3-C2 system in which the mean P-Olsen concentrations in the deeper soil layers (30–60 cm) at F3-C2-ST1, F3-C2-ST2, F3-C2-ST3, F3-C2-ST4, and F3-C2-ST4 sampling locations were 8.3, 13.6, 17.8, 23.0, and 22.2 $\mu\text{g/g}$, respectively. The P-Olsen concentration at the two systems was lower at

location ST1 (distant 3.5 m from the trees) and increased at greater distances from the trees (i.e., 5.0, 6.5, 9.5, and 20 m; Fig. 5a,b). This reduction is attributed to the action of the root system of poplar trees which uptake nutrient quantities. The one-way ANOVA between groups showed that there is statistically significant difference of P-Olsen between sampling sites for the two systems (F3-C1 and F3-C2; Table 3). Post hoc comparison using the Tukey HSD test indicated that the phosphorus concentration at ST1 location of F3-C1 system was significantly lower than the concentrations at ST3, ST4, and ST5. Also, the phosphorus concentration of F3-C2 system at ST1 was significantly lower than the respective values at ST3, ST4, and ST5.

At the surface layers (0–5 and 10–15 cm) of the F3-C1 and F3-C2 systems (Fig. 5c,d), the $\text{NO}_3\text{-N}$ concentrations were greater at the beginning (sampling 1) of the cultivation period, and ranged between 23.9 and 219.2 $\mu\text{g/g}$ and 32.0 and 210.5 $\mu\text{g/g}$, respectively. High nitrogen concentrations were measured in deeper soil layers (55–60 and 75–80 cm) in the two systems, which ranged between 25.0 and 220.2 $\mu\text{g/g}$ for the F3-C1 and 11.4 and 109.1 $\mu\text{g/g}$ for the F3-C2 system; this is due to the great solubility of nitrate nitrogen in the rain and/or irrigation water, and its transport toward the deeper layers. At the end of the cultivation period, lower nitrogen concentrations were measured at the sampling location near the poplar tree row (i.e., location F3-C1-ST1, 15.6 to 29.65 $\mu\text{g/g}$; location F3-C2-ST1, 11.4 to 37.2 $\mu\text{g/g}$; Fig. 5c,d), indicating nitrogen uptaking by the trees. The one-way ANOVA between groups showed that there is statistically significant difference of $\text{NO}_3\text{-N}$ between sampling sites for the two systems (F3-C1 and F3-C2; Table 3). Post hoc comparison using the Tukey HSD test indicated that the nitrate nitrogen concentration at ST1 location of F3-C1 system was significantly lower than the respective values at ST3, ST4, and ST5 locations. Also, the nitrate nitrogen concentration of F3-C2 system at ST1 was significantly lower than the respective concentrations at ST3, ST4 and ST5 locations (Table 3).

Regarding phosphorus, results at all systems showed that at depths 55–60 and 75–80 cm at all sampling locations of all systems, the P-Olsen concentration was lower than that at surface layers (0–5, 10–15, and 30–35 cm). This is graphically shown in Fig. 6, which presents the contours of P-Olsen (first column of graphs) and $\text{NO}_3\text{-N}$ (second column of graphs) iso-concentrations at various distances from the tree row

and various depths for the sampling survey at the end of the cultivation period for all systems. Figure 6 (first column of graphs) shows that in all systems the lowest P-Olsen concentration was at the zone near the tree row.

In contrast to phosphorus, nitrate nitrogen has high mobility in soils due to its high solubility in water. This is obvious in all systems of the present study (Fig. 6, second column of graphs), where the nitrate nitrogen concentrations measured at deeper layers (55–60 and 75–80 cm) at all sampling sites were equal to or greater than those of the surface layers (Figs. 2, 3, and 4), with the exception of sites in the soil zone near the tree row (about 3.0–5.0 m), where the nitrogen concentration at deeper layers was lower than that of the surface (Fig. 6; F1-S, F1-R systems). This is due to the deeper and extensive tree root system, which uptakes increased quantities of nitrogen from the soil (as mentioned

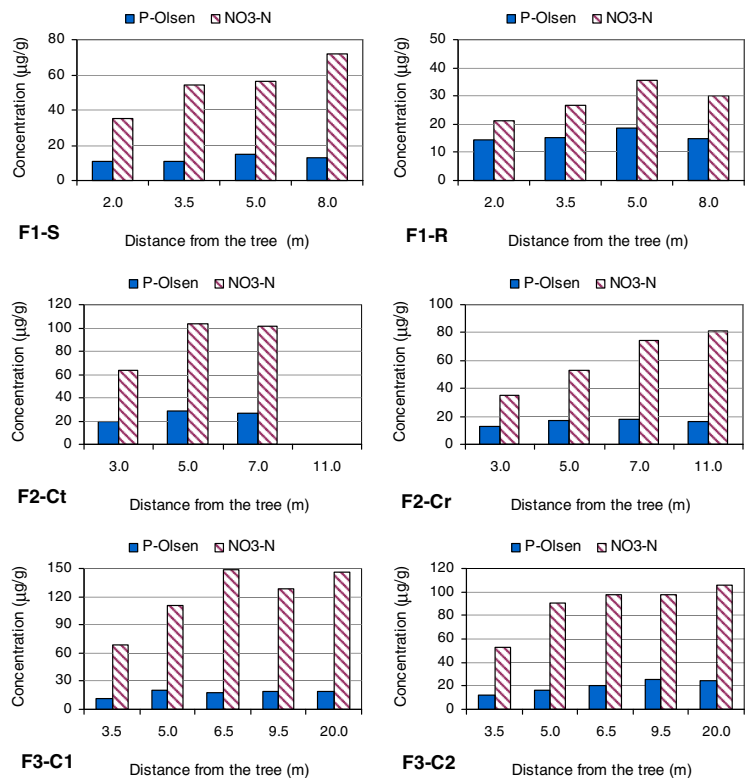
before) compared to monoculture systems. Figure 6 also shows that in all systems the lowest nitrate nitrogen concentration was at the zone near the tree row.

Estimation of nutrient reduction by the tree root system

Figure 7 presents the P-Olsen and NO₃-N depth-averaged concentration in the soil profile at each sampling location of all systems for the entire cultivation period. The depth-averaged concentration was calculated using Eq. (1). For example, at F1-S system, three samples were taken at depths of 0–5, 10–15, and 30–35 cm and the measured P-Olsen concentrations were 29.9, 22.1, and 15.5 μg/g, respectively. In this example, the values of *n*, *d_n*, and *c_i* were: *n*=3, *d_n*=32.5 cm, and *c₁*=29.9, *c₂*=22.1, and *c₃*=15.5 μg/g. Substituting the above values into Eq. (1) yields

$$DAC = \frac{2.5 * 29.9 + \left(\frac{29.9 + 22.1}{2}\right) * (12.5 - 2.5) + \left(\frac{22.1 + 15.5}{2}\right) * (32.5 - 12.5)}{32.5} = 21.8 \text{ } \mu\text{g/g}$$

Fig. 7 Depth-averaged P-Olsen and NO₃-N concentrations at various distances from the tree row for the six experimental systems (F1, F2, F3 experimental fields, S sunflower, R rapeseed, Ct cotton, Cr corn, C1 corn, C2 corn)



At distance of 2.0 m from the tree row of the F1-S system, the P-Olsen and NO₃-N mean concentrations were 10.8 and 35.1 μg/g, respectively. At 3.5, 5.0, and 8.0 m distances from the trees, the nutrient concentrations increased gradually and ranged from 10.8 to 12.8 μg/g for P-Olsen and 54.1 to 72.1 μg/g for NO₃-N, respectively (Fig. 7: F1-S). At distance of 2.0 m from the tree row of the F1-R system, the P-Olsen and NO₃-N concentrations were 14.2 and 21.0 μg/g, respectively. At the remaining sampling locations (i.e., 3.5, 5.0, and 8.0 m from the trees), the P and N concentrations ranged from 14.8 to 18.6 μg/g for P-Olsen and from 26.5 to 35.6 μg/g for NO₃-N, respectively (Fig. 7: F1-R).

In the F2-Ct and F2-Cr systems, at 3.0 m distance from the trees, the P-Olsen concentrations in the soil profile were 19.5 and 12.9 μg/g, respectively, and the NO₃-N concentrations were 63.1 and 35.4 μg/g, respectively (Fig. 7: F2-Ct, F2-Cr). At the other sampling

locations of the F2-Ct system (at distances 5.0 and 7.0 m from the trees), the P-Olsen and NO₃-N concentrations ranged between 26.8 and 28.3 μg/g and 101.3 and 103.4 μg/g, respectively. At sampling locations 5.0, 7.0, and 11.0 m of the F2-Cr system, the P-Olsen and NO₃-N concentrations ranged between 15.9 and 18.0 μg/g and 53.1 and 80.9 μg/g, respectively (Fig. 7: F2-Ct, F2-Cr).

In the F3-C1 and F3-C2 systems, at 3.5 m distance from the trees, the P-Olsen concentrations in the soil profile were 11.6 and 12.4 μg/g, respectively, and the NO₃-N concentrations were 68.4 and 53.3 μg/g, respectively. At sampling locations 5.0, 6.5, 9.5, and 20.0 m of F3-C1 and F3-C2 systems, the P-Olsen concentrations ranged between 17.7 and 19.7 μg/g and 15.9 and 25.1 μg/g, and NO₃-N concentrations ranged between 110.3 and 148.1 μg/g and 90.6 and 105.9 μg/g, respectively (Fig. 7: F3-C1, F3-C2).

Table 4 Phosphorus and nitrogen percent reduction compared to the reference location (most remote from the tree row) in relation to the distance from the tree row

Distance from the tree row (m)	System					
	F1-S	F1-R	F2-Ct	F2-Cr	F3-C1	F3-C2
Phosphorus (P-Olsen)						
2.0	21	15				
3.0			27	24		
3.5	22	8			39	50
5.0	-7	-11	-5	1	2	36
6.5					7	19
7.0			0	-6		
8.0	0	0				
9.5					-3	-1
11.0				0		
20.0					0	0
Nitrogen (NO ₃ -N)						
2.0	45	36				
3.0			38	54		
3.5	16	19			50	47
5.0	12	-9	-2	32	19	11
6.5					-8	4
7.0			0	4		
8.0	0	0				
9.5					7	4
11.0				0		
20.0					0	0

Negative or zero values indicate no effect from the trees

The above results for the mean concentration, and also the statistical analysis presented previously, show that in all systems there is a noticeable difference in phosphorus and nitrogen concentrations between sampling locations located up to a distance of 5.0 m from the tree row, but not beyond this. Therefore, it can be assumed that the influence of the root system of the poplar tree regarding phosphorus and nitrogen removals is minimal or zero at distances greater than about 5 m from the trees. Taking as a reference level for the F1-S system, the average concentrations of P-Olsen and NO₃-N at distances from the tree of 5.0 and 8.0 m, the reduction of phosphorus and nitrogen in the soil zone of 2.0 m from the trees can be calculated at 21 % for P and 45 % for N (Table 4).

For the other systems, the reference level is taken based on the nutrient mean concentration of sampling sites at distances from the tree of 5.0 and 8.0 m for the F1-R system, 7.0 m for the F2-Ct system, 7.0 and 11.0 m for the F2-Cr system, and 9.5 and 20.0 m for the F3-C1 and F3-C2 systems. These are assumed to be locations not influenced by the trees, i.e., control locations. The percent reduction of phosphorus and nitrogen is presented in Table 4 and is attributed to the action of tree root system, given that all the other conditions (i.e., soil properties, rainfall, irrigation, fertilization, etc.) at all sampling locations were the same.

In systems F1 and F2, the effect of trees (20 years old) seems reaching an approximate distance of up to 3.5 m from the tree row while in system F3 it extends up to 6.5 m, something attributed to the older age (30 years) of these trees.

Discussion

The low concentration of P-Olsen at the deeper soil layers in the three fields (F1, F2, F3) is due to low mobility of phosphorus which is adsorbed to the soil. The adsorption of P is enhanced by the high Fe and Al concentrations in the soil, while the organic matter presence plays an important role (Mansell et al. 1995). In the three fields F1, F2, and F3 of this study, the Fe concentration ranged between 13.0 and 32.1 ppm, 9.7 and 17.9 ppm, and 16.9 and 26.2 ppm, respectively, and the organic matter concentration ranged between 0.43 and 1.04 %, 0.41 and 1.05 %, and 0.55 and 1.10 %, respectively (Table 2), conditions that seem to favor the adsorption and retention of phosphorus to the soil

material, resulting to small concentrations in the deeper layers. Similar results to the present study have been reported by other researchers in similar systems. For example, Nair and Graetz (2004) measured at the surface layer (0–5 and 5–15 cm) of a pecan-cotton system in Florida Mehlich 1-P concentration from 30.9 to 71.3 µg/g, values greater than those of the present study (P-Olsen concentration at F2-Ct system ranged from 15.7 to 40.9 µg/g). Of course, concentrations depend on local geo-meteorological and drainage conditions, soil texture, and agricultural practices including quantity and timing of fertilizer application, crop and tree species. Michel et al. (2007) measured phosphorus concentration in the soil profile of silvopastures and treeless pastures in Florida. They found that water-soluble phosphorus in silvopastures was lower compared to treeless pastures systems, and the removal of nutrients from the soil profile were greater near the trees of the silvopastures.

At the deeper soil layers in all systems, the nitrate nitrogen concentrations were not the same. For example, the nitrogen concentration in the F2-Cr system was lower than that in the F3-C1 system (Figs. 4d and 5c). These differences are difficult to interpret because the nitrate nitrogen leaching is also affected by other parameters, such as climatic (e.g., rainfall), soil (e.g., composition, hydraulic conductivity), cultivation conditions (e.g., quantity, type, and timing of application of fertilizer), and processes of nitrogen cycle, such as nitrification and denitrification (Di and Cameron 2002). The nitrate concentration in the soil profile is also affected by water quantity and time and duration of irrigation. Lenka et al. (2013) studied the effect of three different irrigation levels (W1, minimum irrigation; W2, medium irrigation; and W3, maximum irrigation) on soil nitrate accumulation in a maize cropping system. They found that water regimes had a significant effect on soil NO₃-N concentrations at all depths and the peak NO₃-N concentration was observed at 15–30 cm in W1 and W2 regimes and at 30–60 cm in W3 water regime. Therefore, the different nitrate nitrogen concentrations at the deeper soil layers in the studied systems may be due to different quantity of irrigation water applied and to local rainfall depth. The denitrification process contributes to nitrogen loss in the atmosphere in the form of N₂O or/and N₂ and is restricted at low pH (below 7) and low organic carbon (Wang et al. 2011). According to Richards and Colin (1999), the denitrification in the subsoil of agricultural fields largely was inhibited when

the organic carbon ranged between 1.8 and 2.6 g/kg. In the six systems studied in the present study, the mean pH value was lower than 7.8 and the organic carbon concentration ranged from 2.3 to 6.3 g/kg (Table 2), and consequently, the denitrification was limited. Therefore, the reduction of nitrogen is mainly due to uptake by trees and crops.

The results of Table 4 and Fig. 7 show that phosphorus and nitrogen is accumulated in the soil profile during the cultivation period. More amounts of nutrients are accumulated at distance greater of 3.5 m from the trees indicating the effect of tree roots. According to Cambardella et al. (1999), about 50–70 % of nitrogen nitrate accumulated in the soil profile after the cultivation period will be leached during the winter. Therefore, based on Table 4, the nitrate amounts that will be leached from the zone near the trees (about 3.5 to 5 m wide) would be lower compared to those from the zone farther away from the trees. Similar results from the literature clearly show the “safety-net” role of the tree root system underneath the crop roots. For example, Browaldh (1995) studied an agri-silvicultural system of poplar trees with oats and barley in Sweden. He found that the $\text{NO}_3\text{-N}$ concentration was lower near the trees and concluded that the trees reduced the potential for $\text{NO}_3\text{-N}$ leaching. Allen et al. (2004) studied a pecan-cotton alley cropping system in Florida and found that the nitrate nitrogen reduction at a depth of 0.9 m was 34 % compared to a monoculture of cotton. Also, in an acacia-sorghum cropping system, the nitrogen leaching losses were 53 % lower than a sorghum monoculture system (Lehmann et al. 1998). Wang et al. (2011) compared two systems: a citrus tree intercropped with peanut crops and a mono-peanut cropping system in Jiangxi Province, China. In these two systems, they measured nitrate nitrogen concentration in soil water at depths from 0.2 to 0.85 m. The $\text{NO}_3\text{-N}$ concentration ranged between 0.04 and 16.6 mg/L in the citrus-peanut system and between 0.06 and 52.2 mg/L in the mono-peanut cropping system. The lower concentration in the combined system was attributed to the tree root system which extended to a depth of 0.85 m while the peanut crop roots only extended to a depth of 0.2 m. The above studies and our study indicate that the deeper-rooted trees act as a safety net, since they uptake important amounts of nitrogen leaching in deeper soil layers underneath the crops. These findings suggest that experimental tree-crop systems are more efficient in removing nitrogen and phosphorus from the soil profile than

single-crop systems, and therefore, the former might contribute to reducing nonpoint source pollution from reaching to groundwater.

The results of this experimental study confirm the initial hypothesis that the deep roots of trees create a protecting net underneath the root system of the crop, which uptakes excess nutrients, particularly nitrate nitrogen, and blocks them from moving through the vadoze zone and reaching the groundwater table. Also, they show that the creation of tree-crop system with tree rows placed at distances of about 10 m (in the case of poplar trees) may be effective in reducing nutrients and, simultaneously, allowing mechanical cultivation. However, further research into the economic benefits of such systems is probably necessary, something beyond the scope of the present study.

Conclusions

The combined root system of trees and crops in the sunflower-poplar tree (F1-S), rapeseed-poplar tree (F1-R), cotton-poplar tree (F2-Ct) and the corn-poplar tree (F2-Cr, F3-C1, F3-C2) cultivations seem to uptake greater amounts of N and P in comparison to a single cultivation of the same crop (sunflower, rapeseed, cotton or corn) with a shallower root system. Nitrogen showed increased mobility to the deeper soil layers compared to phosphorus. Therefore, N concentrations were greater at the deeper layers. However, in the soil zone near the trees, nitrogen concentrations were lower compared to those at more distant locations from the trees. It seems that tree-crop systems can play a significant role in protecting groundwater quality in intensively cultivated areas under Mediterranean conditions by reducing nitrate migration to groundwaters.

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