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Nitrogen fertilization of poplar plantations on agricultural land: effects on diameter increments and leaching

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ABSTRACT

Fast-growing poplar plantations on agricultural land require intensive management activities, often involving fertilization. The present paper aims at investigating the effect of fertilization on growth and on groundwater quality, by examining four trials established in commercial poplar plantations in central and south Sweden. The treatments consisted of nitrogen applications (Urea N46, Tot. N: 46%) in two different dosages, 75 and 150 kg ha^{-1} for two years, and a control, in three replicates (plot size: 20 × 20 m) following a randomized block design. Diameters were measured at each plot at the end of each growing season for the period 2012–2015. At the same time, groundwater pipes were installed in the center of each plot, at ca. 1.5 m depth. Samples were regularly collected and analyzed for NO_3-N and PO_4-P. The results show a large variation in the diameter growth response to nitrogen fertilization and the leaching of poplar plantations after canopy closure. In young plantations, the effect on growth was clear with moderate fertilization rates although it was not observed on sandy soils with already good growth, leading to high nitrogen leaching.

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Poplar plantations; groundwater; fertilization; nutrient runoff; fast-growing plantations; *Populus* spp.

Introduction

Poplar plantations (*Populus* spp.) have been used as a fast-growing biomass feedstock for both pulp and energy purposes in many European countries (e.g. Isebrands & Richardson 2014). In Sweden, poplars have been grown since the 1980s in small stands on agricultural land in the central and southern parts of the country (Rytter 2004). The most frequent clones and species planted have been the OP-42 (*Populus maximowiczii* Henry × *Populus trichocarpa* Torr. and Gray), followed by balsam poplar (*P. balsamifera* L.) and black cottonwood (*P. trichocarpa*). Although the area planted in the 1980s and 1990s was mostly for demonstration purposes, the growing demand for biomass feedstocks for energy has increased the area planted in Sweden; up to ca. 1000 ha of poplar plantations were reported in 2014 (Nordh et al. 2014), and additional areas are currently being established.

Yield estimations during the 2000s demonstrated the potential of poplar as a viable option for set-aside land in Sweden, when suitable plant material is available for the farmers (Karačić et al. 2003). Rytter (2004) reported biomass levels between 3.2 and 13.6 t ha^{-1} yr^{-1} for different poplar clones and species in Sweden, indicating high variation. As in other fast-growing plantations, management is a critical variable to ensure high production levels (Mola-Yudego et al. 2014). In this sense, poplar may require intensive management practices that often differ from traditional silviculture, such as use of clone material, fertilization, high densities, avoidance of thinning and shorter harvest rotations.

Fertilization is assumed to result in substantial yield increases, but the response of fast-growing *Salicaceae* plants to fertilization has been found to be controversial. In recent studies, Aronsson et al. (2014) and Sevel et al. (2014a) showed a strong response to fertilization regimes increasing the yield levels of fast-growing willow plantations, whereas Quaye and Volk (2013) and Balasus et al. (2012) showed no significant effects of fertilization on willow yields. Despite these discrepancies, nitrogen fertilization has been recommended in practical guidelines to willow growers in Sweden and elsewhere in Europe (Danfors et al. 1997; Gustafsson et al. 2009; Caslin et al. 2010), and it has been assumed to effectively increase yield at least when applied on less-productive agricultural soils (Hofman-Schielle et al. 1999; Labrecque & Teodorescu 2003).

In the case of poplar plantations in Sweden, no such guidelines exist and fertilization of poplar plantations is not common, despite recommendations provided in other countries to fertilize at least during the first years of rapid growth until complete canopy closure (Hansen et al. 1988; Fox et al. 2007). In the case of young plantations intensively fertilized, nitrogen leaching in the groundwater is to be expected (McLaughlin et al. 1985; Balasus et al. 2012; Sevel et al. 2014b), and such negative effects must be avoided. At the same time, willows and poplars grown on agricultural soils have shown lower nutrient leaching to the groundwater (Dimitriou et al. 2009, 2012) compared to other agricultural crops, due to the permanent and deep root system being a perennial crop, and the higher transpiration rates compared to conventional agricultural crops (Dimitriou et al. 2009).

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In this context, the present paper aims at identifying the effects of two fertilization treatments on yield and groundwater quality of four fast-growing poplar plantations on agricultural land studied for several years in central and south Sweden. The main hypotheses assume that: (1) there is a response to fertilization in diameter increment of trees even after canopy closure, (2) the NO_3-N concentrations in groundwater will be low, related to the fertilization effect on growth and, (3) there will be no effect of fertilization on the PO_4-P concentrations in groundwater.

Material and methods

Description of the trials

Fertilization trials were established in four poplar plantations at the locations of *Billinge*, *Stora Vallskog*, *Stöpen* and *Sätuna*, in central and south Sweden (Figure 1). The climatic profiles were extracted from the WorldClim database v1.4 (Hijmans et al. 2005) for the locations of the trials. *Billinge*, *Stora Vallskog* and *Sätuna* were established in 2012, and *Stöpen* in 2013. The spacing was 3 × 3 m. The treatments consisted of nitrogen additions (Urea N46, Tot. N: 46%) in two different dosages, 75 and 150 N kg ha^{-1}, and a non-fertilized control ($n = 3$, plot size 20 × 20 m), following a randomized block design. The treatments were repeated in the following spring. All plantations were in canopy closure at the time of the setup.

The clone that was used was OP-42 (*Populus maximowiczii × trichocarpa*), except for *Stora Vallskog* where *Populus angustifolium* was used (Table 1). The plantations at *Billinge* and *Stöpen* were 10 and 7 years, respectively, and presented a high yield whereas *Stora Vallskog* and *Sätuna* were 21 and 22 years, respectively, with *Stora Vallskog* showing the lowest yield performance. In December 2013, the trial at *Billinge* was severely affected by the storm Sven, which damaged over 30% of the trees in some of the treatment plots, but left some of the remaining plots unaffected. The last measurement from this trial was therefore excluded in the statistical calculations in order to avoid a possible bias.

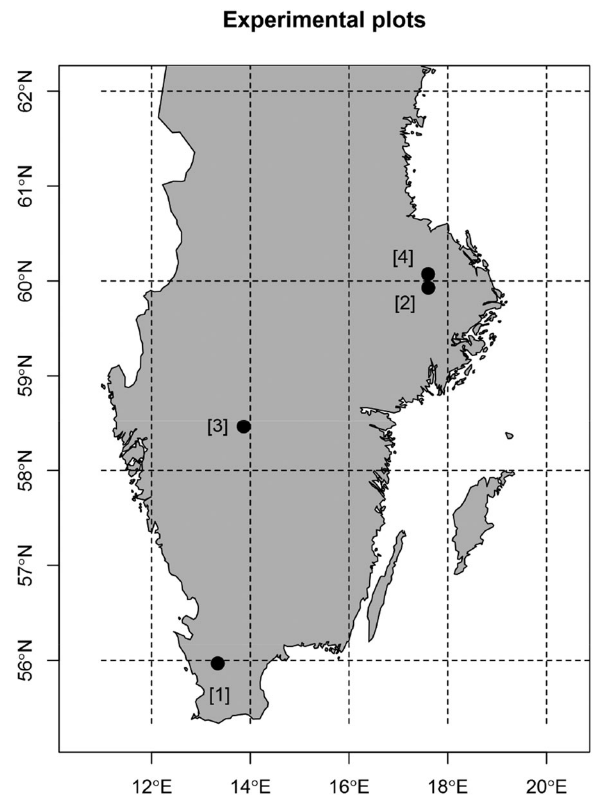

Figure 1. Map of Sweden showing the locations of the studied plantations. [1]: *Billinge*, [2]: *Stora Vallskog*, [3]: *Stöpen*, [4]: *Sätuna*.

Sampling methods

Diameters at breast height (dbh) were measured for each tree in all plots in order to estimate diameter increment before fertilization and during the period 2012–2015. This resulted in four measurements per tree at *Billinge, Stora Vallskog* and *Sätuna* and three measurements at *Stöpen*.

Groundwater pipes were installed at all fields except *Stöpen* in spring 2012: 1 pipe in the center of each plot, thus 9 pipes in each of the three fields ($n = 3$ for each treatment in every field) for a total of 27 pipes installed (Table 1). At each field, holes were drilled down to the groundwater table using an auger and PVC pipes 50 mm diameter and slits up to 0.5 m from the bottom were vertically installed in the holes. The average depth for the pipes was 1.5 m. To prevent clogging with soil particles, the base of each pipe was covered with a fiber cloth up to the slits. The holes were then filled with gravel followed by granulated bentonite clay to prevent short-cut flow of water along the pipe wall. Finally, at the top, an additional 110-mm PVC pipe with a cap was installed around each pipe to prevent contamination.

From each pipe, samples for chemical analyses were taken using a manual vacuum pump. Before sampling, the

Table 1. Description of the poplar plantations included in the study.

Location		Billinge	Stora Vallskog	Stöpen	Sätuna
Lat		55.97	59.93	58.46	60.07
Long		13.34	17.61	13.87	17.6
T_{min} (May)	(°C)	6.7	4.4	4.6	4.4
T_{min} (Sept)	(°C)	9.4	7.9	6.9	7.7
T_{max} (May)	(°C)	14.4	14.8	15.3	14.8
T_{max} (Sept)	(°C)	15.7	14.6	15.1	14.6
P (annual)	(mm)	700	556	612	561
P (May–Sept)	(mm)	285	253	269	253
Year Est.		2002	1991	2006	1990
Age	(yrs)	10	21	7	22
Species/clone		OP-42	*P. angustifolium*	OP-42	OP-42
Soil type		Sand	Silt	Light clay	Light clay
dbh (cm)		17.6	12.6	14.4	27.3
SE dbh	(cm)	0.16	0.29	0.1	0.38
MAI	(cm yr^{-1})	1.8	0.6	2.1	1.2
N		302	147	367	230
Period measured		2012–2015	2012–2015	2013–2015	2012–2015

Notes: Lat, latitude (north); Long, longitude (east); T_{min} and T_{max}, monthly maximum and minimum temperatures; *P*, precipitation. Year Est, year when the plantations was planted; *Age*, years till the first measurement; *dbh*, diameter at breast height at the initial period; *SE*, standard error; *MAI*, mean annual diameter increment; *N*, number of trees measured at the initial period. OP42 (*Populus maximowiczii × trichocarpa*).

groundwater pipes were emptied, and then a 100 ml of the sample of fresh groundwater was collected in a plastic jar. The sampling was conducted according to other studies for groundwater sampling for assessing leaching (Aronsson et al. 2010) and it was done monthly from June 2012 to June 2015. All collected samples were analyzed for NO_3-N (Swedish Standard SS 28133) and PO_4-P (SS-EN ISO 6878:2005). The analyses were based on a spectrophotometric method for quantitative determination using Konelab Aqua 60, and were carried out by *Eurofins Environment Sweden AB*.

Statistical methods

The potential effects of the fertilization treatments on diameter growth were tested using a linear model for each site individually, and a mixed model for all sites combined, in the form:

$$y_{ij} = \text{FERT}_0 + \text{FERT}_{ij} + \mu_j + \mu_{ij}, \quad (1)$$

where *y* is the dependent variable, defined as the mean annual diameter increment relative to the initial diameter of tree *i*, FERT_0 referred to the intercept ($\text{FERT}_0 \times \beta_0$), corresponding to no fertilization, and FERT was defined with two levels for 75 and 150, related to the fertilization dosage and expressed as a dummy variable, in the form $\text{FERT}_{75} \times \beta_{75}$ and $\text{FERT}_{150} \times \beta_{150}$ (FERT adopting values of 0 and 1, and β being the parameter). μ are random factors, normally distributed and with mean = 0. When all data are combined, μ_j is the random factor referring to the effect of trees growing on site *j* and μ_{ij} is the error term.

In the case of NO_3-N and PO_4-P concentrations, there were several measurements taken in a given date. In this case, a linear model was built for each site individually and afterwards a model was constructed for all sites combined. Given the structure of the data, a generalized mixed model approach was taken, in which a fixed effect (the mean concentrations for a given treatment) and a random effect (grouping all the measurements taken the same day) were combined. And additional random factor related to the *site* was considered but the resulting models did not converge, due to the excessive amount of parameters to be fitted

$$\ln(y_{it}) = \text{FERT}_0 + \text{FERT}_i + \mu_t + \mu_{it}, \quad (2)$$

where *y* is the dependent variable, defined as the concentration on water of NO_3-N and PO_4-P, which presented a non-normal distribution including many zero values. Therefore, the effect was modeled after a *Poisson* distribution, and the dependent variable (*y*) was considered as a continuous variable using the logarithmic link function and the rounded value of the concentration expressed in 10^{-2} g l^{-1} on a pipe *i* for time *t*. FERT was defined as in [1]. The grouping levels were defined using μ_t for time and μ_{it} for the error term. The calculations were based using the package *lme4* (Bates et al. 2015) using the statistical software R v3.1.2 (R development core team 2014). Finally, a variation of the

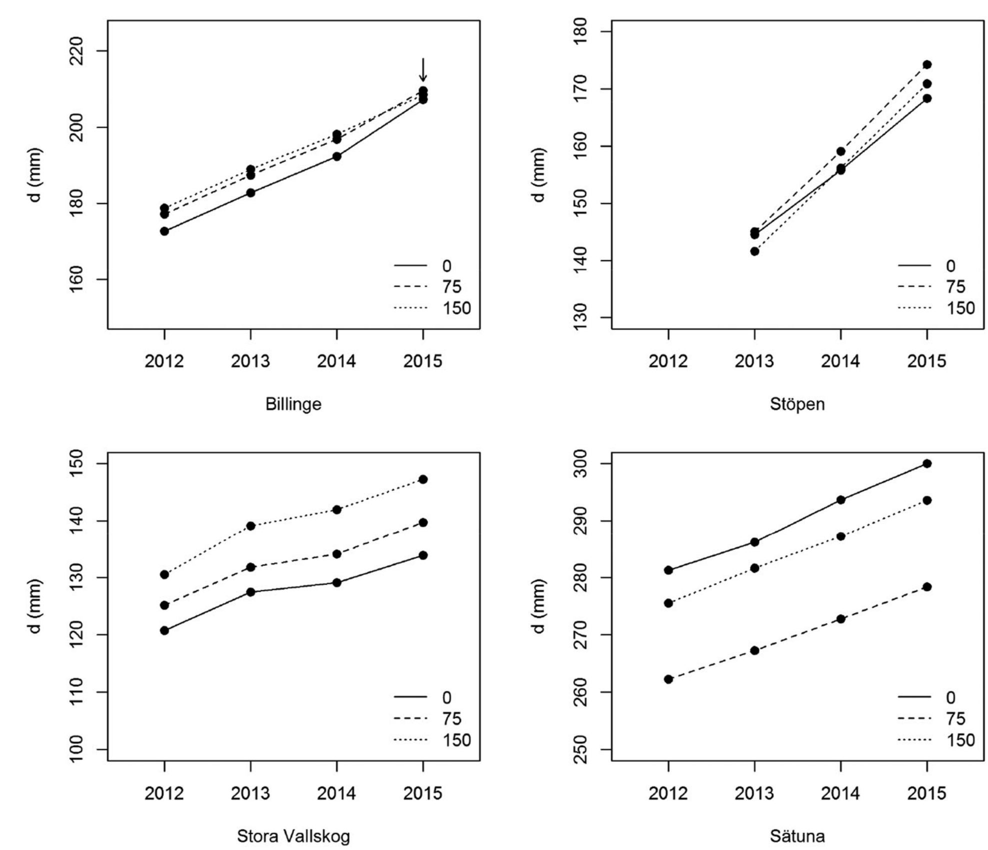

Figure 2. Mean diameter for the four sites analyzed by fertilization treatments (0: no fertilization, 75, 150 kg N ha^{-1}). The legend refers to the amount of fertilization applied (kg N ha^{-1}), 0: control. A storm affected the plantation at *Billinge*, affecting several trees unevenly among treatment units, and modifying the growth patterns in the subsequent growing season (see arrow).

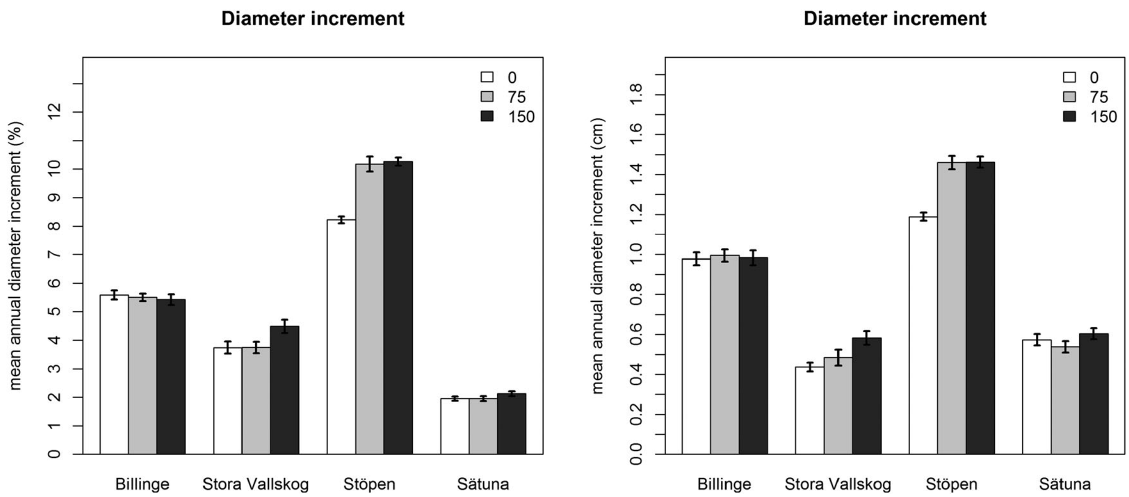

Figure 3. Mean annual diameter increment of the poplar sites, as a percentage of the initial diameter (left) and the actual increment (right), according to the fertilization treatments (0: no fertilization, 75, 150 kg N ha^{-1}). *Billinge* entails 2012–2014, *Stöpen* entails 2013–2015, *Stora Vallskog* and *Sätuna* entail 2012–2015. Error bars represent the standard error of the mean.

model [2] was used to test seasonal effects in the concentrations, by including a dummy variable for spring measurements.

Results

The mean diameter along time for the four sites analyzed showed different trends by treatment. There was a fast diameter increment at *Stöpen* ("young plantation on clay"), whereas it was more moderate at *Billinge* ("young plantation on sand") and *Stora Vallskog* ("old plantation on silt"), being the slowest at *Sätuna* ("old plantation on clay") (Figure 2). It also must be noticed that although initial diameters were not the same, no systematic trend was observed between treatments. To avoid any effects of these variations, the percentage of diameter increment with respect to the initial

Table 2. Results of the statistical analysis for diameter, and concentrations of NO_3-N and PO_4-P in groundwater.

Diameter (Beta values)	Billinge	Stora Vallskog	Sätuna	Stöpen	All
$FERT_0$	**5.60**	**3.74**	**1.95**	**8.21**	**4.77**
SE	*0.16*	*0.22*	*0.08*	*0.19*	1.60
p-Value	<.001	<.001	<.001	<.001	.003
$FERT_{75}$	−0.09	0.002	0.00	**1.95**	**0.66**
SE	*0.23*	*0.30*	*0.11*	*0.27*	0.13
p-Value	.677	.995	.998	<.001	<.001
$FERT_{150}$	−0.17	**0.74**	0.17	**2.04**	**0.81**
SE	*0.23*	*0.20*	*0.12*	*0.27*	0.13
p-Value	.452	.016	.141	<.001	<.001
σ_{site}					3.20
NO_3-N	Billinge	Stora Vallskog	Sätuna		All
$FERT_0$	**3.389**	−0.205	**4.320**		**2.23**
SE	*0.487*	*0.454*	*0.273*		0.48
p-Value	<.001	.652	<.001		<.001
$FERT_{75}$	**0.575**	−0.907	−0.631		0.42
SE	*0.025*	*0.482*	***0.065***		**0.02**
p-Value	<.001	.060	<.001		<.001
$FERT_{150}$	**1.102**	0.096	−1.851		0.90
SE	*0.021*	*0.458*	***0.102***		**0.02**
p-Value	<.001	.210	<.001		<.001
σ_{time}	2.048	2.220	0.520		2.598
PO_4-P	Billinge	Stora Vallskog	Sätuna		All
$FERT_0$	**−1.500**	0.479	−0.337		**−0.93**
SE	*0.381*	*0.258*	*0.447*		0.33
p-Value	<.001	.064	.452		.004
$FERT_{75}$	−1.449	0.115	−0.511		**−0.45**
SE	*0.764*	*0.279*	*0.730*		0.21
p-Value	.058	.679	.484		.034
$FERT_{150}$	−0.740	0.514	−0.357		−0.14
SE	*0.501*	*0.278*	*0.671*		0.21
p-Value	.140	.065	.595		**0.496**
σ_{time}	0.636	0.684	n.a.		1.393

Notes: Diameter refers to the mean annual diameter increment of the poplar trials, as a percentage of the initial diameter, for three treatments expressed in N kg ha^{-1}, and analyzed as a linear model for the individual sites, and as a linear mixed model for the combined measurements (All), using *site* as a grouping factor. NO_3-N and PO_4-P were analyzed using a generalized mixed effects model, using a *Poisson* distribution of the concentration (10 g l^{-1}). The grouping factor was time of the measurements (along the period 2012–2015). SE: Standard error. σ_{time} refer to the standard deviations of the random factor. Significant values are highlighted (bold) and the standard errors (italics).

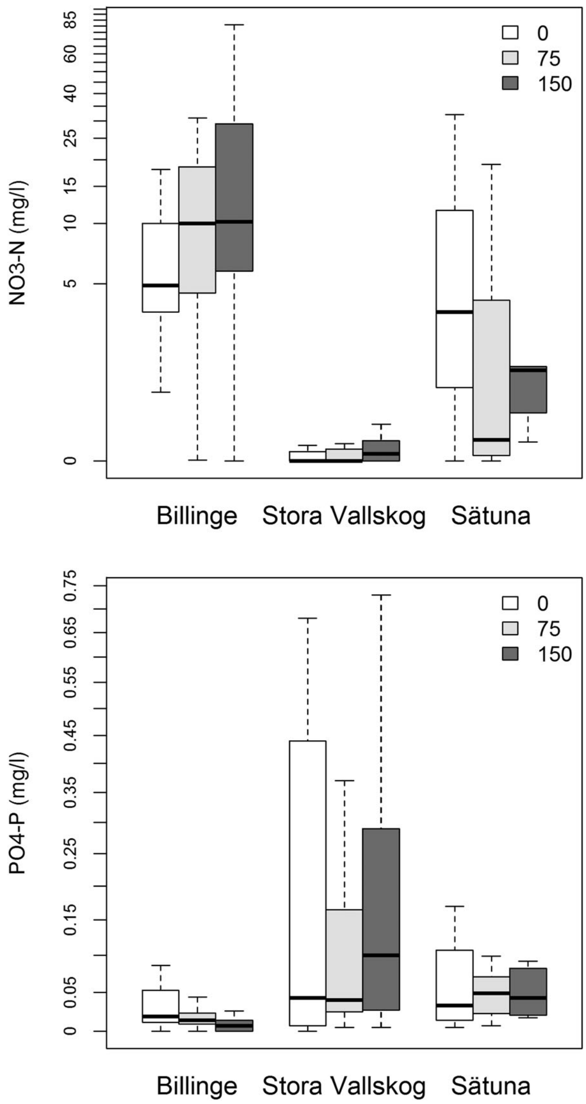

Figure 4. Concentrations of NO_3-N (left) and PO_4-P (right) in the groundwater of the poplar sites by site and treatment (0: no fertilization, 75 , 150 kg N ha^{-1}). The boxes represent the median, upper and lower quartiles, and the bars the maxima and minima excluding outliers. The values are represented in logarithmic scale.

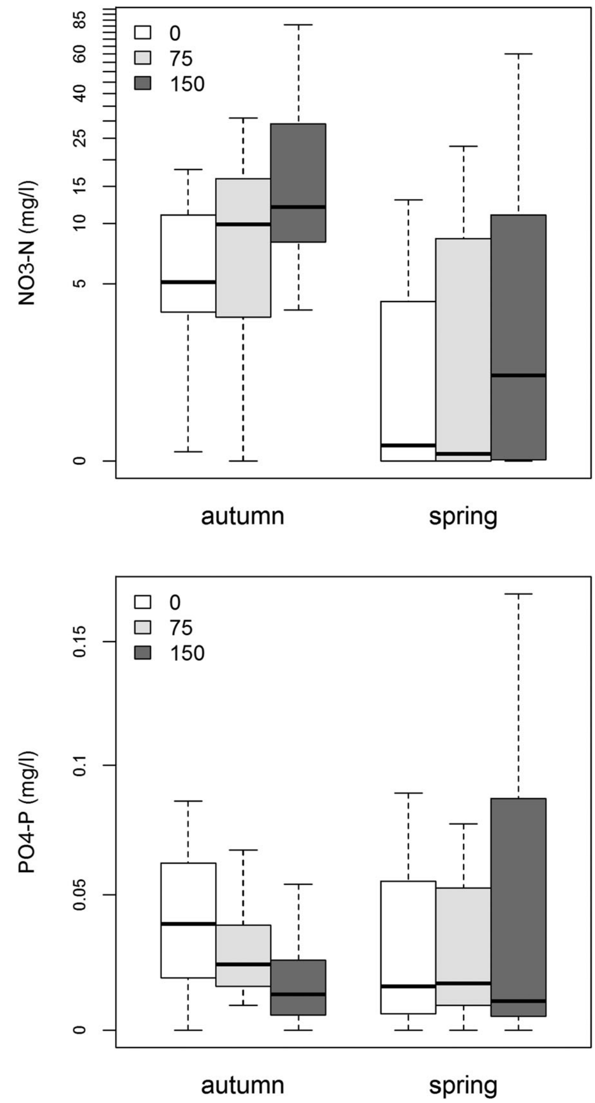

Figure 5. Concentrations of NO_3-N and PO_4-P in the groundwater of the poplar trials by treatment (0: no fertilization, 75, 150 kg N ha^{-1}), during spring (March until June) and autumn (September until December) based on the trials at *Stora Vallskog* and *Billinge.* The boxes represent the median, upper and lower quartiles, and the bars the maxima and minima excluding outliers. The values are represented in logarithmic scale.

diameter was calculated, as it was considered a better indicator to assess the treatment effects (Figure 3).

The results show that the mean annual diameter increment for all plantations and treatments was 5.95%, and the effects of fertilization had an overall effect on diameter growth when taken together. However, there was a large variation between sites (Figure 3); for instance, *Stöpen* presented the highest annual increment (9.57%) and *Sätuna* the lowest (2.01%), with significant differences between sites (p-values $< .001$ for all combinations). Trees at *Stöpen* responded similarly to both fertilization treatments, with high increments in growth. In the case of *Stora Vallskog* the effect was observed only in the case of the most intensive treatment (150 kg N ha^{-1}). Finally, at *Billinge* and *Sätuna*, treatments did not have statistically significant effects on the diameter growth (Table 2).

Concerning groundwater concentrations, in some cases measurements could not be retrieved as there was no water available in the pipe system by the time of the sample. When taken all sites together, the treatment effect on NO_3-N concentration in the groundwater was significant (Table 2), but also in this case each site responded in a different way. High concentrations were found particularly in the most intensive fertilization treatment at the *Billinge* site (Figure 4). Overall, lower concentrations were identified at *Sätuna* and particularly low at the *Stora Vallskog* site. Attending to the treatments, significant differences were found in Billinge and *Sätuna*, although of opposite sign (Table 2), and no effect was observed at *Stora Vallskog*. Concerning PO_4-P, no statistical differences were evident between the different treatments in any sites (Figure 4). Among fields, the PO_4-P concentrations were the highest in the groundwater at *Stora Vallskog* and the lowest at the *Billinge* site.

For all measurements combined, concentrations of NO_3-N in the groundwater in spring were lower than in autumn (p-value $< .001$), and no differences were found concerning PO_4-P (Figure 5). By treatments, there were seasonal

Table 3. Results of the statistical analysis for seasonal concentrations of NO_3-N and PO_4-P in groundwater for three treatments expressed in N kg ha^{-1}.

	NO_3-N	PO_4-P
$FERT_0$	3.606	−0.684
SE	0.706	0.507
p-value	<.001	.177
$FERT_{75}$	0.510	−0.252
SE	0.033	0.336
p-value	<.001	.454
$FERT_{150}$	1.051	−0.811
SE	0.028	0.521
p-value	<.001	.119
$FERT_{0\ (spring)}$	−2.128	−0.314
SE	0.893	0.628
p-value	.017	.617
$FERT_{75\ (spring)}$	−0.179	−0.330
SE	0.046	0.438
p-value	<.001	.451
$FERT_{150\ (spring)}$	−0.302	0.794
SE	0.039	0.571
p-value	<.001	.164
σ_{time}	2.336	1.360

Note: The effect is analyzed using a generalized mixed effects model, using a *Poisson* distribution of the concentration (10^{-1} g l^{-1}). The grouping factor was time of the measurements. SE: standard error. σ_{time} refer to the standard deviations of the random factor.

differences in all the treatments in the case of concentrations of NO_3-N (Table 3), and no seasonal effect was observed concerning PO_4-P.

Finally, the realizations of the random factor used (the values of μ_{time} for each measurement event) showed a descending pattern in the case of the Billinge site for NO_3-N, and no clear structure in the other cases (Figure 6).

Discussion

Our results show a nitrogen fertilization effect in two of the four poplar plantations included (*Stora Vallskog* and *Stöpen*). The magnitude of the effect greatly varied among sites, being the largest at *Stöpen* related to the highest dosage. In the same way, previous studies on nitrogen fertilization of poplar plantations have also reflected different effects; it has been reported to increase poplar growth (Czapowskyj & Safford 1993; Heilman & Xie 1993; Brown & van den Driessche 2002, 2005; Coleman et al. 2006), but also a limited or no effect on hybrid poplar height and diameter (van den Driessche et al. 2005; DesRochers et al. 2007). These variety of responses can be linked to several factors such as the age of the plantations, the number of years of the applications, the fertility of the sites, the clones used and combinations of these. In fact, the plantations included in the study include different ages and soil conditions, entailing the ranges are common in the Swedish plantations (Johansson & Karačić 2011; Hjelm et al. 2015; Dimitriou & Mola-Yudego 2016) and reflecting the current conditions of the cultivation. To observe a clear systematic effect may therefore require a larger sample of plantations in order to assess how the response is affected by age and soil.

Most of the research concerning nitrogen fertilization refers to fertilization applications before or close to canopy closure, which would be in line with the results observed at *Stöpen*. In this way, fertilization avoids weed competition while providing N, which is usually the most limiting factor to growth (e.g. Fox et al. 2007; Stanturf & van Oosten 2014), at a stage of critical need. In fact, Czapowskyj and Safford (1993), Brown and van den Driessche (2002) and Coleman et al. (2006) reported significantly increased biomass production in poplar plantations when nitrogen was provided to poplars near canopy closure compared to unfertilized controls.

Concerning older plantations, the highest nitrogen fertilization treatment at *Stora Vallskog* had an effect on growth, but in far lesser degree at *Sätuna*. To our knowledge, very few studies have reported experiments for fertilizing poplars of an age that exceeded 10 years; as an example Grau Corbí et al. (1997) showed that nitrogen fertilization resulted in 18–37% increase of the increment in 12-year-old poplar plantations in Spain, which are higher than the values observed in the results. Likewise, similar increases for nitrogen fertilized 12-year-old hybrid aspens were reported (Stanturf & van Oosten 2014).

The yields in the plantation at Sätuna, which was of similar age to Stora Vallskog (ca. 22 years), were much higher compared to the ones at Stora Vallskog, which can explain the differences in the response, as they indicate that the plant material was more appropriate to the soil and climatic conditions. *Populus angustifolia* was established at *Stora Vallskog*, which is a species not known for being

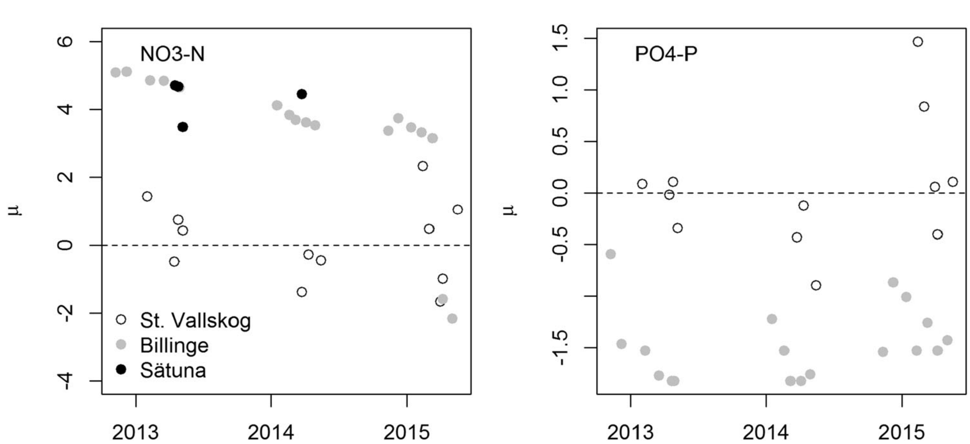

Figure 6. Values of the realizations of the random factor in the models for concentrations of NO_3-N and PO_4-P in the groundwater of the poplar trials. The data from *Sätuna* did not converge for PO_4-P.

productive under Swedish conditions and has mainly been used for ornamental purposes. It can be therefore concluded that nitrogen fertilization can have an effect in older poplar plantations with initial low growth, but the effect is likely to be clone-specific, as several authors have shown earlier (Hakulinen et al. 1995; Karačić & Weih 2006; Stanturf & van Oosten 2014). In this sense, the non-significant fertilization effect at *Sätuna* compared to the other fields can be explained by the already rather high yields performed before fertilization occurred, indicating that site-specific conditions were adequate for high yields even without fertilization.

The plantation at *Stöpen* was young but also fertilized after canopy closure, and showed a clear nitrogen fertilization effect even with the lower fertilization rate and despite the relative high growth of the plants. The plantation at *Billinge* was of similar age to the one in *Stöpen*, however, no fertilization effect was observed. In this case, the plantation was established on a sandy soil, which usually implies higher leaching than in clay soils (Mortensen et al. 1998; Dimitriou et al. 2009, 2012), as it was the case in our study, and can reduce the nitrogen use by the plant. At the same time, growth was already relatively high in the plantation at *Billinge*, which may indicate lower nitrogen needs and therefore no effect of nitrogen fertilization (see also Stanturf & van Oosten 2014).

In our study, nitrogen concentrations in the groundwater at *Stora Vallskog* and *Sätuna* ("old plantations") did not differ substantially between the different treatments and the control and were close to zero throughout the whole period. At the *Billinge* site, however, leaching was relatively high even in the control treatment, and increased with increased nitrogen amounts applied. At the same time, the models showed that the average leaching values were decreasing from the time of fertilization. This effect can be attributed as previously mentioned to the sandy soil at *Billinge*, and it was more pronounced when the plantations were fertilized (Jørgensen 2005; Dimitriou & Aronsson 2010). In this respect, fast-growing tree plantations of willow and poplar grown on agricultural soils have been identified as a means of reducing leaching in the groundwater of agricultural landscapes even when intensively managed (Dimitriou et al. 2009, 2012; Dimitriou & Rosenqvist 2011; Syswerda & Robertson 2014). In some cases poplars have even been identified being more effective in reducing nitrogen leaching even compared with willows (Palmer et al. 2014), which are widely known for showing minimal leaching from sites applied with large amounts of nitrogen (Dimitriou et al. 2009; Aronsson et al. 2010). The results of this study do not fully support this claim, as leaching can be significant, and the interactions with soil must be further explored. Finally, the observed decreasing trend in nitrogen concentrations along time in Billinge is difficult to interpret: it could indicate an effective and progressive reduction in the nitrogen concentrations after the fertilization treatments, or perhaps it is a consequence of the storm affecting the site, which affected the treatment design and could explain the different pattern in the random factor realizations.

The lack of treatment effects on PO_4-P concentrations in groundwater was not surprising since no phosphorus was applied to the fertilized plots. However, willow plantations grown on agricultural soils have been reported to have higher PO_4-P concentrations in groundwater than adjacent reference fields even when not fertilized with P, and this have been potentially attributed to the rooting system of perennial crops that go deeper enabling preferential flow of soil particles with bound phosphorus particles further facilitated due to their root channels, especially on clay soils (Dimitriou et al. 2012). This was not the case in the fields of our study, except for *Stora Vallskog* where PO_4-P concentrations in groundwater were higher in the control poplar plots than an adjacent to the poplar plantation field.

In summary, our results show that the response of poplar plantations to nitrogen fertilization, measured as growth and leaching after canopy closure, varied markedly. Fertilization affected diameter growth even on mature plantations when growth conditions have been poor. However, the results show a possible soil–age interaction, as a result, future fertilization recommendations for poplar plantations should be site and stand age-specific to prevent negative effects on the groundwater quality.

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References

Aronsson P, Dahlin T, Dimitriou I. 2010. Treatment of landfill leachate by irrigation of willow coppice – plant response and treatment efficiency. Environ Pollut. 158:795–804. doi:10.1016/j.envpol.2009.10.003

Aronsson P, Rosenqvist H, Dimitriou I. 2014. Impact of nitrogen fertilization to short-rotation willow coppice plantations grown in Sweden on yield and economy. BioEnergy Res. 7:993–1001. doi:10.1007/s12155-014-9435-7

Balasus A, Bischoff WA, Schwarz A, Scholz V, Kern J. 2012. Nitrogen fluxes during the initial stage of willows and poplars in short-rotation coppices. J Plant Nutr Soil Sci. 175:729–738. doi:10.1002/jpln.201100346

Bates D, Maechler M, Bolker B, Walker S. 2015. Fitting linear mixed-effects models using lme4. J Stat Softw. 67:1–48.

Brown KR, Van den Driessche R. 2002. Growth and nutrition of hybrid poplars over 3 years after fertilization at planting. Can J For Res. 32:226–232. doi:10.1139/x01-191

Brown KR, Van den Driessche R. 2005. Effects of nitrogen and phosphorus fertilization on the growth and nutrition of hybrid poplars on Vancouver Island. New For. 29:89–104. doi:10.1007/s11056-004-5418-4
Caslin B, Finnan J, Mc Cracken A. 2010. Short rotation Willow Coppice guidelines. Teagasc, ISBN 1-84170-568-3.
Coleman M, Tolsted D, Nichols T, Johnson WD, Wene EG, Houghtaling T. 2006. Post-establishment fertilization of Minnesota hybrid poplar plantations. Biomass Bioenergy. 30:740–749. doi:10.1016/j.biombioe.2006.01.001
Czapowskyj MM, Safford LO. 1993. Site preparation, fertilization, and 10-year yields of hybrid poplar on a clearcut forest site in eastern Maine, USA. New Forests. 7:331–344. doi:10.1007/BF00036753
Danfors B, Ledin S, Rosenqvist, H. 1997. Energiskogsodling. Handledning för odlare (Growers manual, in Swedish). JTI informerar. Nr 1997;1, Uppsala.
DesRochers A, Van Den Driessche R, Thomas BR. 2007. The interaction between nitrogen source, soil pH, and drought in the growth and physiology of three poplar clones. Botany. 85:1046–1057. doi:10.1139/B07-062
Dimitriou I, Aronsson P. 2010. Landfill leachate treatment with willows and poplars – Efficiency and plant response. Waste Manag. 30:2137–2145. doi:10.1016/j.wasman.2010.06.013
Dimitriou I, Busch G, Jacobs S, Schmidt-Walter P, Lamersdorf N. 2009. A review of the impacts of Short Rotation Coppice cultivation on water issues. Landbauforschung – vTI Agric For Res 3:197–206.
Dimitriou I, Mola-Yudego B. 2016. Poplar and willow plantations on agricultural land in Sweden: Area, yield, groundwater quality and soil organic carbon. For Ecol Manag. doi:10.1016/j.foreco.2016.08.022
Dimitriou I, Mola-Yudego B, Aronsson P. 2012. Impact of willow Short Rotation Coppice on water quality. Bioen Res. 5:537–545. doi:10.1007/s12155-012-9211-5
Dimitriou I, Rosenqvist H. 2011. Sewage sludge and wastewater fertilisation of Short Rotation Coppice (SRC) for increased bioenergy production—biological and economic potential. Biomass Bioenergy. 35:835–842. doi:10.1016/j.biombioe.2010.11.010
Fox TR, Allen HL, Albaugh TJ, Rubilar R, Carlson CA. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. Southern J Appl Forestry. 31:5–11.
Grau Corbí JM, González Antoñanzas F, Montoto JL. 1997. Influencia de la fertilización N-P-K sobre el crecimiento y producción de choperas plantadas a raíz profunda en la cuenca del Duero. Actas II Congreso Forestal Español IRATI. Pamplona, 23-27 Junio. 1997. Tomo III, pp. 283-288. ISBN: 84-235-1592-3.
Gustafsson J, Larsson S, Nordh NE. 2009. Manual for SRC Willow Growers. Lantmännen Agroenergi, Sweden, 18 p. Available from: http://www.voederbomen.nl/wordpress/wp-content/uploads/2012/08/ManualSRCWillowGrowers.pdf (Accessed: 29/7/2015)
Hakulinen J, Julkunen-Tiitto R, Tahvanainen, J. 1995. Does nitrogen fertilization have an impact on the trade-off between willow growth and defensive secondary metabolism? Trees, 9:235–240. doi:10.1007/BF00195278
Hansen E, McLaughlin R, Pope P. 1988. Biomass and nitrogen dynamics of hybrid poplar on two different soils: implications for fertilization strategy. Can J For Res. 18:223–230. doi:10.1139/x88-033
Heilman PE, Xie F. 1993. Influence of nitrogen on growth and productivity of short-rotation Populus trichocarpa Populus deltoides hybrids. Can J For Res. 23:1863–1869. doi:10.1139/x93-236
Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. Int J Climatol. 25:1965–1978.
Hjelm B, Mola-Yudego B, Dimitriou I, Johansson T. 2015. Diameter–height models for fast-growing poplar plantations on agricultural land in Sweden. Bioen Res. 8:1759–1768. doi:10.1007/s12155-015-9628-8
Hoffmann-Schielle C, Jug A, Makeschin F, Rehfuess KE. 1999. Short rotation plantations of balsam poplar, aspen and willows on former arable land in the Federal Republic of Germany. I. Site-growth relationships. For Ecol Manag. 121:41–55. doi:10.1016/S0378-1127(98)00555-6
Isebrands JG, Richardson J. 2014. Poplars and willows: trees for society and the environment. CABI. doi:10.1079/9781780641089.0000
Johansson T, Karačić A. 2011. Increment and biomass in hybrid poplar and some practical implications. Biomass Bioenergy. 35:1925–1934. doi:10.1016/j.biombioe.2011.01.040
Jørgensen U. 2005. How to reduce nitrate leaching by production of perennial energy crops? In: Zhu Z, Minami K, Xing G, editors. 3rd international nitrogen conference, contributed papers. Monmouth Junction, NJ: Science Press, Nanjing, China; p. 513–518.
Karačić A, Weih M. 2006. Variation in growth and resource utilisation among eight poplar clones grown under different irrigation and fertilisation regimes in Sweden. Biomass Bioenergy. 30:115–124. doi:10.1016/j.biombioe.2005.11.007
Karačić A, Verwijst T, Weih M. 2003. Above-ground woody biomass production of short-rotation Populus plantations on agricultural land in Sweden. Scand J For Res. 18:427–437. doi:10.1080/02827580310009113
Labrecque M, Teodorescu TI. 2003. High biomass yield achieved by Salix clones in SRIC following two 3-year coppice rotations on abandoned farmland in southern Quebec, Canada. Biomass Bioenergy. 25:135–146. doi:10.1016/S0961-9534(02)00192-7
McLaughlin RA, Hansen EA, Pope PE. 1987. Biomass and nitrogen dynamics in an irrigated hybrid poplar plantation. For Ecol Manag. 18:169–188. doi:10.1016/0378-1127(87)90159-9
Mola-Yudego, B., Dimitriou, I., Gonzalez-Garcia, S., Gritten, D., Aronsson, P. 2014. A conceptual framework for the introduction of energy crops. Ren Ener. 72:29–38. doi:10.1016/j.renene.2014.06.012
Mortensen J, Nielsen KH, Jørgensen U. 1998. Nitrate leaching during establishment of willow (Salix viminalis) on two soil types and at two fertilization levels. Biomass Bioenergy. 15:457–466. doi:10.1016/S0961-9534(98)00056-7
Nordh NE, Norberg I, Paulrud S. 2014. JTI-INFORMERAR JTI:s skriftserie 2014:1. (In Swedish).
Palmer MM, Forrester JA, Rothstein DE, Mladenoff DJ. 2014. Conversion of open lands to short-rotation woody biomass crops: site variability affects nitrogen cycling and N2O fluxes in the US Northern Lake States. GCB Bioen. 6:450–464. doi:10.1111/gcbb.12069
Quaye AK, Volk TA. 2013. Biomass production and soil nutrients in organic and inorganic fertilized willow biomass production systems. Biomass Bioenergy. 57:113–125. doi:10.1016/j.biombioe.2013.08.002
R Development Core Team. R, 2014. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.
Rytter L. 2004. Production potentials of aspen, birch and alder – a review on possibilities and consequences of harvest of biomass and merchantable timber. Skogforsk–Redogörelse nr 2004:4, pp 64 (In Swedish with English summary).
Sevel L, Ingerslev M, Nord-Larsen T, Jørgensen U, Holm PE, Schelde K, Raulund-Rasmussen, K. 2014a. Fertilization of SRC willow, II: leaching and element balances. Bioen Res. 7:338–352. doi:10.1007/s12155-013-9371-y
Sevel L, Nord-Larsen T, Ingerslev M, Jørgensen U, Raulund-Rasmussen K. 2014b. Fertilization of SRC Willow, I: biomass production response. Bioen Res. 7:319–328. doi:10.1007/s12155-013-9371-y
Stanturf J, van Oosten C. 2014. Poplars and willows: trees for society and the environment. Cabi International. Edited by Isebrands J.G., Richardson, J. ISBN: 978 1 78064 108 9, pp. 200–257.
Syswerda SP, Robertson GP. 2014. Ecosystem services along a management gradient in Michigan (USA) cropping systems. Agric Ecosys Envir. 189:28–35. doi:10.1016/j.agee.2014.03.006
van den Driessche R, Niemi F, Charleson L. 2005. Fourth year response of aspen seedlings to lime, nitrogen and phosphorus applied at planting and one year after planting. For Ecol Manag. 219:216–228. doi:10.1016/j.foreco.2005.08.047