Macronutrient leaching in a fertilized juvenile hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) plantation cultivated in an agroforestry system in Latvia

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ABSTRACT

Leaching of macronutrients such as nitrogen, phosphorus and potassium from soils is of particular interest in the Baltic Sea region because of its adverse effects on water quality. The objective of this study was to evaluate macronutrient leaching in a juvenile hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) plantation cultivated in an agroforestry system and fertilized with biogas production residues, wastewater sludge and wood ash in hemi-boreal climate conditions. Analysis of macronutrient concentrations in the soil solution showed that annual macronutrient leaching decreased over time after the establishment of the plantation and application of fertilizers. Moreover, macronutrient leaching was affected not only by meteorological conditions, but also by the type of fertilizer used. During the five years after establishment of the plantation, nitrate-nitrogen leaching decreased up to 99.6%, phosphate-phosphorus leaching decreased up to 97.1%, but potassium ions leaching decreased up to 76.5%. Nevertheless, juvenile hybrid aspen plantations cultivated in an agroforestry system remain an important part in mitigation of leaching of macronutrients from agricultural lands in the Baltic Sea region.

Key words | agroforestry system, hybrid aspen, macronutrient, mitigation of leaching

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INTRODUCTION

Plantations characterized by high yields, such as short rotation forestry (SRF), are becoming popular worldwide for biomass production, and their role in sequestering carbon is acknowledged in the Kyoto Protocol (Calfapietra *et al.* 2010). In the Baltic and Nordic countries, where forestry has traditionally been oriented towards long rotation periods (commonly 50–120 years), SRF is a new silvicultural concept with rotation periods of less than 30 years (Tullus *et al.* 2012). Agroforestry is a unique land use system that intentionally blends perennial vegetation and herbaceous land cover types to enhance crop productivity and profitability while providing wildlife habitat and maintaining biodiversity (Altieri 1999), enrich soils (particularly in terms of carbon sequestration) and reduce erosion (Lenka *et al.* 2012), enhance microbial communities in soil (Banerjee *et al.* 2015), and enhance soil, air and water quality in agro-ecosystems overall (Jose 2009; Baah-Acheamfour *et al.* 2015). In agroforestry systems, trees constitute a significant avenue of organic matter (and nutrient) addition to the soil ecosystem (Haile *et al.* 2008; Takimoto *et al.* 2008; Isaac *et al.* 2011).

The most common species utilized for agroforestry plantations in temperate and boreal climates belong to the genera *Populus* and *Salix* (Calfapietra *et al.* 2010). Hybrid aspen (*P. tremula* L. × *P. tremuloides* Michx.) is a man-made hybrid between the European aspen and the North American trembling aspen (Koivuranta *et al.* 2012). In the

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Baltic Sea region, hybrid aspen is one of the most promising trees for biomass production due to its high growth rate (Yu *et al.* 2001; Tullus *et al.* 2012; Jansons *et al.* 2014). Hybrid aspen plantations are expanding in the Scandinavian and Baltic countries (Koivuranta *et al.* 2012). In Northern Europe during recent decades, about 4,500 ha of hybrid aspen have been cultivated for both experimental and practical purposes. In Latvia, breeding and selection work on hybrid aspen started in the 1960s, stopped, then restarted in 2003 when joint stock company (JSC) 'Latvia's State Forest' and Latvian State Forest Research institute 'Silava' (LSFRI Silava) showed new interest in hybrid aspen (Jansons *et al.* 2014; Smilga *et al.* 2015). About 500 ha of hybrid aspen plantations have been established in Latvia, mainly on abandoned agricultural lands (Tullus *et al.* 2012). Recently, hybrid aspen was included in a major national breeding programme for economically important trees in Latvia (Jansons 2008).

In the Baltic Sea and North Sea regions, concerns over deteriorating water quality in both freshwater and marine waters and eutrophication of surface waters initiated a call for action (e.g., Helsinki Convention, Oslo-Paris Convention (OSPAR), Nitrates Directive (91/676/EEC)) against nutrient pollution (Andersen *et al.* 2014; Bechmann *et al.* 2014). Nevertheless, climatic changes influence the possibilities for agricultural production (e.g., longer growing seasons), agricultural management practices (e.g., changes in tillage, fertilization, increase in dose of fungicides) and runoff conditions, and thereby the losses of nutrients from agricultural lands to the environment (Øygarden *et al.* 2014; Huttunen *et al.* 2015). The mitigation of leaching losses of nutrients is an important ecosystem service, and is easily affected by small-scale management decisions (Tully *et al.* 2012).

Agroforestry practices are also a proven strategy to provide clean water (Jose 2009). Agroforestry systems have been proposed as a means to combat non-point source pollution from agricultural fields (Udawatta *et al.* 2002; Lee *et al.* 2003; Anderson *et al.* 2008; Jose 2009) and help clean runoff by reducing its velocity, thereby promoting infiltration, sediment deposition and nutrient retention. Agroforestry systems also reduce nutrient movement into groundwater by nutrient uptake by roots (Lee *et al.* 2003; Allen *et al.* 2004; Nair & Graetz 2004; Jose 2009). These nutrients are then recycled back into the system through root turnover and litterfall, increasing the nutrient use efficiency of the system (Allen *et al.* 2004; Jose 2009). Trees also have a longer growing season than most agricultural crops, which increases nutrient use and use efficiency in an agroforestry system by capturing nutrients before and after the cropping season (Jose 2009). Overall, the current evidence suggests that agroforestry systems could play a substantial role in mitigating water quality issues arising from intensive agricultural practices (Jose 2009). Dimitriou *et al.* (2009) emphasize the point that groundwater quality is positively affected, in particular, by hybrid aspen plantations when compared with the cultivation of annual crops, but large plantations of fast-growing trees consume large amounts of groundwater and thus could have negative effects on regional hydrology (Busch 2009). In the past two decades, hybrid aspen has been extensively utilized in the phytoremediation of a broad range of organic and inorganic (i.e., heavy metal) contaminants in soils (Marmiroli *et al.* 2013; Mukherjee 2014; Valujeva *et al.* 2016).

The aim of a circular economy is to utilize industrial and urban waste (Ghisellini *et al.* 2016), biogas production residues (digestate), wastewater sludge and wood ash used as fertilizers and other uses where a 'Safe return to the Biosphere or in a cascade of subsequent uses' is possible (EMF 2012). However, the use of biogas production residues, wastewater sludge and wood ash application as fertilizer can cause environmental risks such as nutrient leaching and contamination with heavy metals (Chang *et al.* 1984; Nasreddine & Parent-Massin 2002; Lofts 2007; Alhadrami *et al.* 2016).

The objective of this study was to evaluate macronutrient leaching in a juvenile hybrid aspen (*P. tremula* L. × *P. tremuloides* Michx.) plantation cultivated in an agroforestry system and fertilized with biogas production residues ($30\ \mathrm{t\ ha^{-1}}$), wastewater sludge ($10\ \mathrm{t_{DM}\ ha^{-1}}$) and wood ash ($6\ \mathrm{t_{DM}\ ha^{-1}}$) in hemi-boreal climate conditions using an integrated approach of empirical measurements and modelling.

STUDY AREA AND DATA

Study site

Research was carried out in the central part of Latvia (Figure 1). An experimental plot (latitude: 56.6919 N,

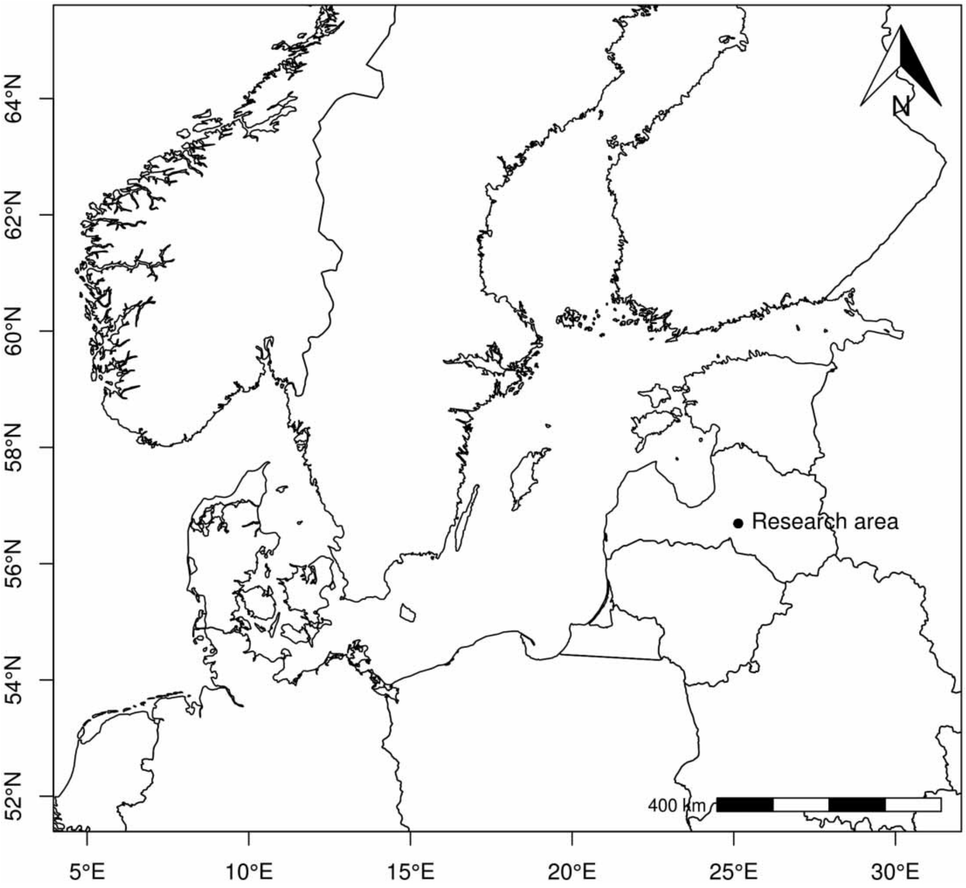

Figure 1 | Location of the study site.

longitude: 25.1370 E) was established on agricultural land in spring 2011. The experimental plot of hybrid aspen (*P. tremula* L. × *P. tremuloides* Michx.) is a part of a large-scale multifunctional plantation of short rotation energy crops and deciduous trees with a total area of 16 ha. The type of soil is classified as *Luvic Stagnic Phaeozem (Hypoalbic)* or *Mollic Stagnosol (Ruptic, Calcaric, Endosiltic)* according to the FAO (2006) with the dominant loam (at 0–20 cm depth) and sandy loam (at 20–80 cm depth) soil texture. The plantation was fenced in autumn 2012.

Design and planting material

In 2011, hybrid aspen (*P. tremula* L. × *P. tremuloides* Michx.) seedlings (clone No. 4), originating from JSC 'Latvia's State Forest', Latvia, were planted with an average distance between the trees of 2.5 × 5.0 m and 2.0 × 2.0 m. Between the 5 m tree rows, two legume and two perennial grass cultivars were sown for seed production: fodder galega (*Galega orientalis* Lam.) 'Gale', poor-alkoloid lupine (*Lupinus polyphyllus* L.) 'Valfrids', reed canary grass (RCG) (*Phalaris arundinacea* L.) 'Bamse' and festulolium (×*Festulolium pabulare*) 'Felina'. The grasses and the legumes were placed in 2.5 m wide columns and the size of one plot was 60 m^2. A free space of 1.25 m between the trees and grass lines was provided. Grasses and legumes were sown using narrow row spacing (12 cm) for RCG and festulolium, and broad row spacing (36 cm) for galega and lupine.

Treatments

Four replications of four different fertilization subplots were conducted: control (no fertilization), wastewater sludge, wood ash and digestate. The size of each subplot was

30 × 24 m, and they were established in the spring of 2011. Class I (according to regulations of the Cabinet of Ministers of the Republic of Latvia No. 362) wastewater sludge (dose 10 t_{DM} ha^{-1}) from 'Aizkraukles ūdens' (Aizkraukle Water) and stabilized wood ash from the boiler house in Sigulda (dose 6 t_{DM} ha^{-1}) were spread mechanically before the planting of hybrid aspen and sowing of legumes and perennial grasses. Digestate (as a point source fertilizer, dose 30 t ha^{-1}) from the methane reactor in Vecauce district (Latvia) was applied immediately after planting of the hybrid aspen seedlings. The input of nutrients is summarized in Table 1. The heavy metal target values and precautionary limits were not exceeded in fertilized soils according to legislative regulations for soil and ground quality (Regulations of the Cabinet of Ministers of the Republic of Latvia No. 804).

Bulk deposition and soil solution sampling and chemical analyses

Soil solutions were sampled in 14 subplots with soil solution samplers (suction tube lysimeters, Eijkelkamp), with soil solution sampler cups made of porous ceramic (92% pure Al_2O_3) and a body of trace metal-free PVC. Soil solution samplers were installed vertically into the soil in each subplot at 60 cm depth in summer 2011. Soil solutions were sampled twice a month during the frost-free period. Bulk deposition was sampled with a continuously open plastic funnel connected to the sample bottle. The funnel also collected parts of particulate and gaseous deposition during dry periods. Bulk deposition was sampled in six subplots twice a month during the whole year (Clarke *et al.* 2016).

The soil solution and bulk deposition samples were analysed in the Forest Environment Laboratory at the LSFRI Silava. The following chemical parameters were measured in the water samples: nitrate-nitrogen (NO_3^--N) concentration determined using FORMACS^{HT} TOC/TN Analyzer (ND25 nitrogen detector); phosphate-phosphorus (PO_4^{3-}-P) determined using an ammonium molybdate spectrometric method according to ISO 6878 and potassium (K) determined using a flame emission spectrometric method according to ISO 9964-3:2000.

Table 1 | Macronutrient input through fertilization

Fertilizer	N_{total}, kg ha^{-1}	P_{total}, kg ha^{-1}	K_{total}, kg ha^{-1}
Wood ash	2.6	65	190
Sewage sludge	259	163	22
Digestate	69	1.2	99

Modelling of groundwater

Since the monitoring plots of the agroforestry system were developed on an existing drainage system, it was impossible to collect drainage water samples from each fertilization subplot. For the understanding of the agroforestry system and the impact of biogas production residues, wastewater sludge and wood ash application on environmental quality, modelling tools were used to calculate daily nutrient loss. The modelling flowchart of subsurface runoff and nutrient leaching is presented in Figure 2.

The input data consisted of two data matrices. The first data matrix consisted of daily climate data: air temperature, precipitation and humidity, from the nearest meteorological station Skriveri operated by State Ltd. 'Latvian Environment, Geology and Meteorology Centre'. The climate data statistics from the year 2011 to 2015 are presented in Table 2. The mean annual air temperature in the time period between 2011 and 2015 ranged from 6.0 to 7.6 °C at the study site, and the annual rainfall ranged from 653 to 935 mm. The second data matrix was the daily soil solution concentrations of NO_3^--N, PO_4^{3-}-P and potassium (K). Missing data were filled using a linear interpolation method.

The conceptual hydrological model METQ was used to calculate daily upper layer subsurface runoff (Krams & Ziverts 1993; Ziverts & Jauja 1999). Parameters for the Daugava river basin hilly agricultural land were used to calibrate hydrological response units of the METQ model (Ziverts & Jauja 1999).

Nutrient leakage was calculated by multiplying the nutrient daily concentrations of the soil solution samples with the daily upper layer subsurface runoff.

Statistical analysis

The data of soil solution chemical composition were divided into four groups according to differences in fertilizer source. Considering that there were no statistically significant

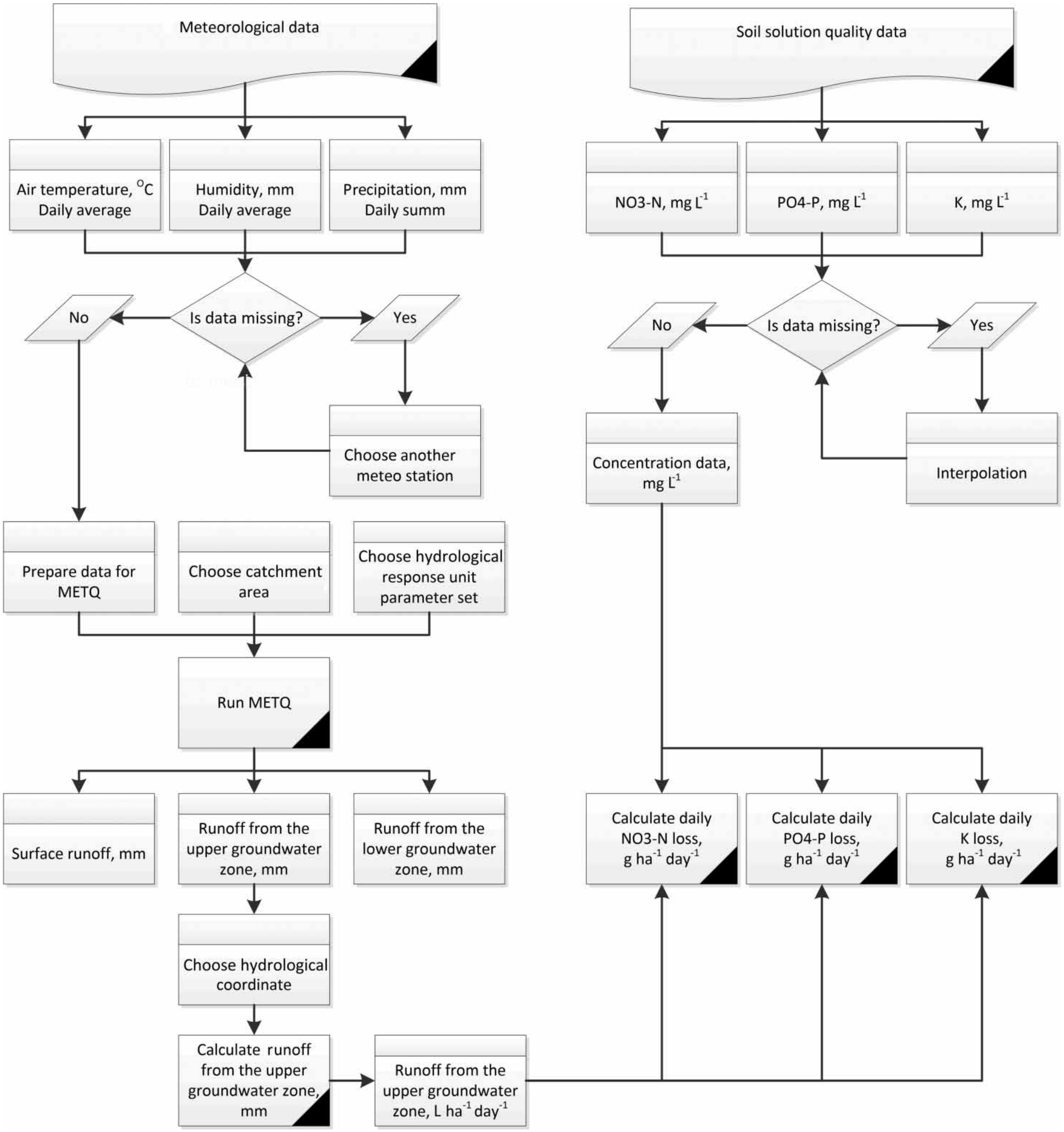

Figure 2 | The modelling flowchart of daily nutrient loss.

differences between the chemical parameters of soil solution in subplots with different planting design (2.5 × 5.0 m and 2.0 × 2.0 m), studied data from subplots with different planting design were combined.

Data processing was performed in OpenOffice 4.1.1 Calc and R (R Core Team 2017). The differences of statistics in macronutrient concentration in soil solutions between different years within treatments were analysed with the

Table 2 | Average monthly air temperature (AT, °C) and precipitation (P, mm month^{-1}) at the study site

		Month											
Year	**P or AT**	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**
2011	P	77.3	39.4	18.4	27.5	54.4	33.5	71.2	133.9	83.3	45.3	41.4	67.1
	AT	−3.6	−9.5	−0.7	7.8	12.0	17.7	20.2	16.9	12.7	7.2	3.5	1.6
2012	P	60.8	39.8	31.7	58.6	121.2	90.7	163.0	45.4	62.9	111.2	96.4	53.7
	AT	−4.0	−9.7	0.8	6.6	12.3	14.3	18.3	15.8	12.7	6.5	3.6	–5.1
2013	P	47.8	34.0	12.7	54.1	71.5	40.8	65.8	75.6	83.5	42.4	76.1	48.2
	AT	−7.2	−2.5	−5.9	4.4	15.7	18.2	18.2	17.1	11.8	7.8	4.2	1.5
2014	P	49.3	34.7	63.4	36.4	104.3	112.0	62.4	179.1	27.7	105.7	31.6	48.9
	AT	−6.5	0.3	3.7	8.0	12.7	14.0	19.8	17.1	12.5	6.0	1.8	−1.5
2015	P	93.8	24.3	56.3	64.6	62.0	47.4	105.6	21.2	79.9	10.0	71.1	51.2
	AT	−1.2	−0.7	3.7	6.5	10.6	14.5	16.3	18.0	12.8	4.8	3.7	2.3

Wilcoxon signed rank test with continuity correction, but differences in macronutrient concentration in soil solutions between treatments within year were analysed with the Wilcoxon rank sum test with continuity corrections.

RESULTS AND DISCUSSION

Changes of macronutrient concentration in bulk deposition and soil solution

The nutrient export from ecosystems is probably enhanced by the combination of inputs from fertilization and from wet deposition (Povilaitis *et al.* 2014). The characterization of the mean annual monitored macronutrient concentration in bulk deposition (2012–2015, January–December) is presented in Table 3. There are no statistically significant differences in the mean annual macronutrient (NO_3^--N, PO_4^{3-}-P and K) concentration in bulk deposition between different study years ($p > 0.05$). The annual average NO_3^--N input via atmospheric deposition on the plots during 2012–2015 was 3.6 kg ha^{-1} yr^{-1}, atmospheric PO_4^{3-}-P input was 0.3 kg ha^{-1} yr^{-1} and annual K input was 2.4 kg ha^{-1} yr^{-1}. Since 2013 (two years after the establishment of experimental plantation and application of fertilizers), NO_3^--N input via atmospheric deposition exceeded NO_3^--N leaching from the agricultural land. Also, the annual average PO_4^{3-}-P input via atmospheric deposition exceeded PO_4^{3-}-P leaching from soils, except the experimental plots fertilized with sewage sludge. This indicates intensive NO_3^--N and PO_4^{3-}-P cycling into the ecosystem and effective uptake of the excess NO_3^--N and PO_4^{3-}-P by the roots of the trees and other plants present.

Agriculture has been identified as one of the main drivers of excessive nutrient inputs into surface waters in the Nordic and Baltic countries. Besides hydro-meteorological conditions, nutrient concentrations in agricultural streams and rivers may vary and respond differently to levels in fertilizer application, type of agricultural management practices (e.g., soil tillage), crop types and intensity of land use (Pengerud *et al.* 2015). The mitigation of leaching losses of nutrient in agricultural lands is one of the ecosystem benefits provided by agroforestry systems, and is easily affected by small-scale management decisions (Tully *et al.* 2012).

The monitoring data of soil solution quality show substantial differences in the levels of macronutrient concentrations among treatments and in the years after the establishment of the hybrid aspen plantation. Changes in the annual average monitored macronutrient concentration in soil solution at 60 cm depth during the study period (2011–2015) are shown in Table 3.

The results of NO_3^--N concentration in soil solution at 60 cm depth show that the highest NO_3^--N concentration was found in 2011 in all treatments (Table 3). NO_3^--N concentration in all treatments decreased logarithmically over time (Figure 3), reaching significant levels (from annual mean 11.0 ± 1.7 mg L^{-1} in 2011 to 0.08 ± 0.02 mg L^{-1} in 2015). The developed models, describing changes in nitrate

Table 3 | The mean (±S.E.) annual macronutrient concentration in bulk deposition and soil solution

		Soil solution			
Year	**Bulk deposition (total input, kg ha^{-1})**	**Control**	**Wood ash**	**Digestate**	**Sewage sludge**
NO_3^--N, mg L^{-1}					
2011	–	16.73 ± 1.97	9.81 ± 2.82	13.00 ± 5.17	8.92 ± 2.86
2012	0.59 ± 0.07 (4.4)	0.60 ± 0.24*	0.51 ± 0.13*	0.52 ± 0.15*	1.02 ± 0.46*
2013	0.57 ± 0.09 (3.7)	0.21 ± 0.11*	0.47 ± 0.14*	0.28 ± 0.06*	0.50 ± 0.14*
2014	0.44 ± 0.06 (2.8)	0.62 ± 0.33*	0.22 ± 0.05*	0.08 ± 0.02*/**	0.29 ± 0.08*
2015	0.54 ± 0.07 (3.4)	0.15 ± 0.05*	0.06 ± 0.02*/**	0.06 ± 0.03*	0.06 ± 0.03*
PO_4^{3-}-P, mg L^{-1}					
2011	–	0.027 ± 0.012	0.039 ± 0.023	0.044 ± 0.021	0.073 ± 0.014
2012	0.05 ± 0.03 (0.3)	0.039 ± 0.011	0.030 ± 0.010	0.033 ± 0.011	0.072 ± 0.017
2013	0.06 ± 0.03 (0.4)	0.028 ± 0.011	0.075 ± 0.031	0.070 ± 0.053	0.097 ± 0.029
2014	0.04 ± 0.02 (0.2)	0.048 ± 0.011	0.033 ± 0.009	0.007 ± 0.001**	0.146 ± 0.025*/**
2015	0.03 ± 0.01 (0.2)	0.014 ± 0.002	0.039 ± 0.006**	0.002 ± 0.001**	0.136 ± 0.026*/**
K, mg L^{-1}					
2011	–	4.45 ± 2.26	7.77 ± 1.78	3.92 ± 0.88	4.43 ± 1.34
2012	0.27 ± 0.08 (2.1)	1.79 ± 0.60	6.12 ± 1.43**	2.15 ± 0.20	1.97 ± 0.46
2013	0.47 ± 0.12 (2.5)	1.69 ± 0.53	4.80 ± 0.95**	2.81 ± 0.70	1.97 ± 0.25
2014	0.22 ± 0.05 (1.5)	2.10 ± 0.31	5.11 ± 0.93**	2.62 ± 0.24	2.00 ± 0.34
2015	0.50 ± 0.11 (3.4)	1.49 ± 0.56	4.95 ± 0.83**	2.65 ± 0.30**	2.35 ± 0.36**

*Significant differences from 2011 within treatment.

**Significant differences between treatment and control within year.

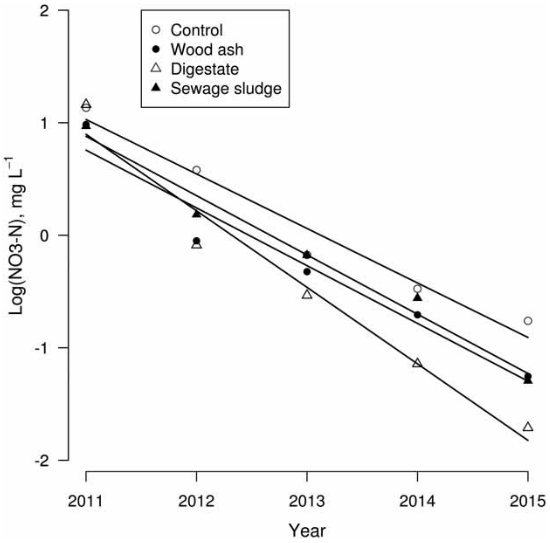

Figure 3 | Changes of nitrate-nitrogen concentration in soil solution over time after fertilization and planting of hybrid aspen seedlings in the study area. Coefficients and main statistics for developed equations are shown in Table 4.

concentration in soil solution on the time period after fertilization and planting of hybrid aspen seedlings, were significant (p-values <0.001), and model residuals corresponded to a normal distribution. The regression equations (models) differed according to type of fertilization (Table 4).

The limiting values of nitrate-nitrogen (11.3 mg NO_3^--N L^{-1}), as defined by the Nitrate Directive, were often exceeded in the small catchment and drainage runoff from fields with intensive farming in the Baltic states (Janson *et al.* 2011). In our study area, the limit concentrations of nitrate-nitrogen were exceeded only during 2011, reaching maximum NO_3^--N extreme (29.8 mg L^{-1}) in the plot fertilized with digestate.

Compared with the control, sewage sludge treatment showed significantly higher annual mean PO_4^{3-}-P concentrations in soil solution in 2014 and 2015 (Table 3). In addition, in the sewage sludge treatment, significantly higher annual mean PO_4^{3-}-P concentrations were found in

Table 4 | Coefficients and main statistics for developed equations of logarithm of nitrate concentration in soil solution (60 cm depth) based on time duration after hybrid aspen planting (as Log NO_3^--N concentration (mg L^{-1}) = ax + intercept, where x is TP (time after planting of hybrid aspen seedlings, days) and a is coefficient value)

	Coeff. ± S.E. (*p*-value)			
Main statistics	**Control**	**Wood ash**	**Digestate**	**Sewage sludge**
Intercept	1.00 ± 0.01 (<0.001)	0.65 ± 0.02 (<0.001)	0.75 ± 0.02 (<0.001)	0.85 ± 0.01 (<0.001)
TP	$-1.34 \cdot 10^{-3} \pm 0.01 \cdot 10^{-3}$ (<0.001)	$-1.34 \cdot 10^{-3} \pm 0.02 \cdot 10^{-3}$ (<0.001)	$-1.75 \cdot 10^{-3} \pm 0.02 \cdot 10^{-3}$ (<0.001)	$-1.45 \cdot 10^{-3} \pm 0.01 \cdot 10^{-3}$ (<0.001)
F-statistic	$1.03 \cdot 10^4$ (<0.001)	6,937 (<0.001)	8,528 (<0.001)	8,538 (<0.001)
R-squared	0.87	0.81	0.84	0.86
Residual S.E.	0.25	0.30	0.35	0.27

Equations describe changes of nitrate-nitrogen concentration in soil solution during time after hybrid aspen planting in agricultural land (time period from August 2011 to December 2015).

soil solutions in 2014 and 2015 compared with the mean PO_4^{3-}-P concentration in soil solution in 2011, pointing to a gradual decomposition of organic fertilizers.

The highest mean annual K concentrations during 2011–2015 were observed in the plots fertilized with wood ash, showing it had a significant impact on K concentration in soil solution (Table 3). The highest K concentration (21.4 mg L^{-1}) in soil solution was observed in the beginning of summer 2012 in the wood ash treatment.

Macronutrient leaching from soil

Latvia is situated in a humid and moderately mild climatic region where rainfall exceeds evaporation, resulting in percolation losses from the soil during spring and autumn (Jansons *et al.* 2011). Numerous studies in the Baltic and Nordic countries have demonstrated that losses of nutrient from agricultural land to water can be substantial (Povilaitis *et al.* 2014); moreover, an increasing trend of nutrient leaching was found in the Baltic countries. This is related to intensification of agriculture in the Baltic countries (Stålnacke *et al.* 2014). In addition, climate change is expected to increase temperature and annual precipitation for the entire Nordic–Baltic region (IPCC 2013). Based on the established relationships between precipitation and runoff, it can be assumed that increased precipitation may increase annual and, especially, winter runoff, which again would increase both nutrient leaching from agricultural areas and natural background leaching in the Baltic Sea catchment (Øygarden *et al.* 2014; Huttunen *et al.* 2015). Attempts to reduce agricultural nutrient losses have been on the political agenda in the Nordic–Baltic countries for several years (Andersen *et al.* 2014).

Using an integrated approach of modelling and empirical measurements, daily mean nitrogen leaching from our study area during 2011–2015 was evaluated and is presented in Figure 4. The highest daily NO_3^--N leaching was observed in 2011 in the plots fertilized with digestate (412.0 g ha^{-1} d^{-1}) and in the control plots (372.4 g ha^{-1} d^{-1}). The annual average NO_3^--N leaching from the study area decreased rapidly from 9.85 kg ha^{-1} yr^{-1} in 2012 to 0.17 kg ha^{-1} yr^{-1} in 2015 (Table 5). According to Jansons *et al.* (2003) and Lagzdins *et al.* (2012), nitrogen losses in Latvia may vary from 2 to 30 kg N ha^{-1} per year, but in the study by Jansons *et al.* (2011), the annual total N losses' variation from diffuse pollution sources in agricultural land in Latvia shows a narrower range from 4.6 to 17.9 kg ha^{-1} yr^{-1}. Bechmann *et al.* (2014) compared N losses from the Nordic–Baltic catchments and found large variations for the period 2007–2011. The Norwegian catchments had the highest losses, varying from 23.8 kg N ha^{-1} to 89.1 kg N ha^{-1} in agricultural areas. In Denmark, the losses varied between 5.7 and 17.7 kg N ha^{-1}, and in Sweden the losses varied from 8.5 up to 35.4 kg N ha^{-1}. For Finland, Lithuania and Latvia, losses ranged between 6.5 and 18.6 kg N ha^{-1}, with most of them in the lower range (Bechmann *et al.* 2014; Øygarden *et al.* 2014).

Daily mean phosphate-phosphorus leaching from the study area during 2011–2015 is presented in Figure 5. The results indicated that the highest daily PO_4^{3-}-P leaching from the study area (11.0 g ha^{-1} d^{-1}) was observed in 2014 (three years after application of fertilizer) in the plots

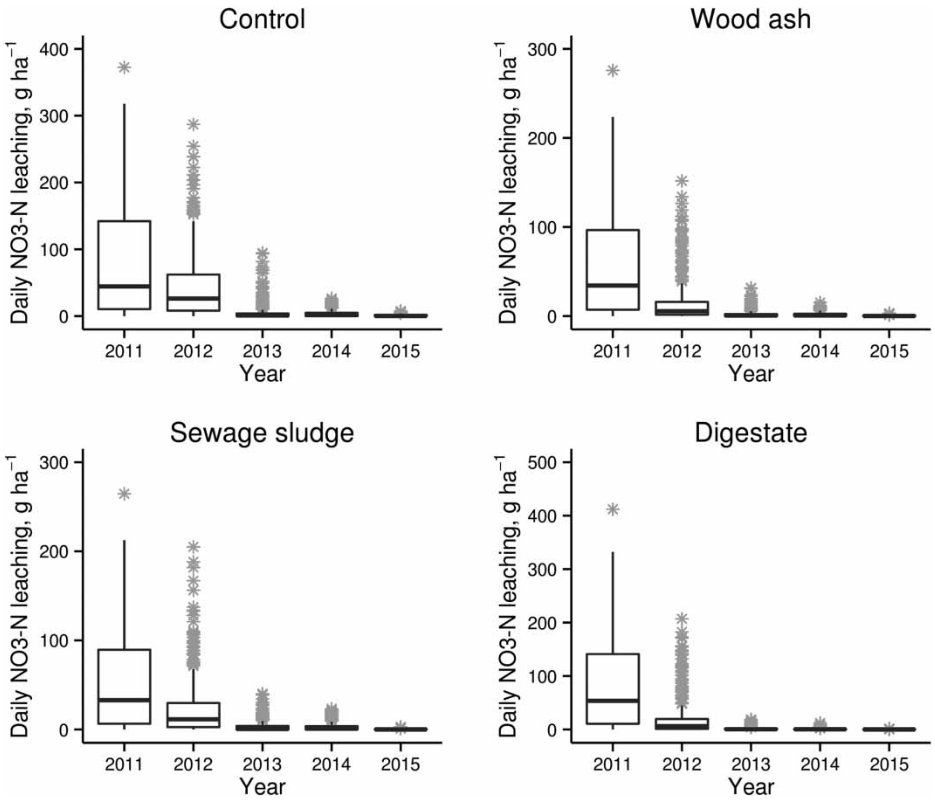

Figure 4 | Daily mean nitrate-nitrogen leaching from the study area during 2011–2015. In the boxplots, the median is shown by the bold line, the box corresponds to lower and upper quartile, whiskers show minimum and maximum values (within 150% of interquartile range from the median) and grey stars represent outliers of the datasets.

Table 5 | Annual average amount of macronutrients leaching from the study area

Macronutrient, unit	Year	Control	Wood ash	Digestate	Sewage sludge
NO_3^-N, kg ha^{-1} yr^{-1}	2012	16.48	6.07	7.88	8.97
	2013	1.78	0.73	0.56	1.26
	2014	1.16	0.64	0.27	0.99
	2015	0.39	0.13	0.06	0.11
PO_4^{3-}-P, g ha^{-1} yr^{-1}	2012	229.7	156.3	64.9	264.7
	2013	192.9	163.5	25.4	148.2
	2014	179.5	136.3	17.8	389.8
	2015	28.0	69.2	6.6	307.5
K, kg ha^{-1} yr^{-1}	2012	13.25	24.87	10.36	9.73
	2013	3.85	10.19	6.07	3.92
	2014	5.69	15.27	8.68	5.87
	2015	3.12	9.26	5.85	4.63

fertilized with sewage sludge. The results indicate a significant effect of sewage sludge fertilization not only on daily mean phosphate-phosphorus leaching, but also on annual mean PO_4^{3-}-P leaching (Table 5). The annual average PO_4-P leaching showed a downward trend during 2012–2015 in control plots and plots fertilized with wood ash and digestate; but in the plots fertilized with sewage sludge, annual mean PO_4^{3-}-P leaching increased in the fourth and fifth years after fertilization, reaching the highest values in the study period (respectively, 389.8 g ha^{-1} yr^{-1} and 307.5 g ha^{-1} yr^{-1}). Pengerud *et al.* (2015) evaluated temporal trends in phosphorus concentrations and losses from agricultural catchments in the Nordic and Baltic countries. Their study shows that the mean annual total P losses range from 7.5 kg total P ha^{-1} yr^{-1} in the Norwegian catchment Vasshaglona to ~0.1 kg total P ha^{-1} yr^{-1} in the catchment Vienziemite (Latvia), where there is only 5–10% of arable land within the catchment and the agricultural land is used mainly as pasture or perennial grassland.

Potassium (K) is a mobile ion in soils and, consequently, significant amounts can be lost by leaching (Alfaro *et al.* 2004). A number of factors influence the movement of K in soils, including the cation exchange capacity, soil pH

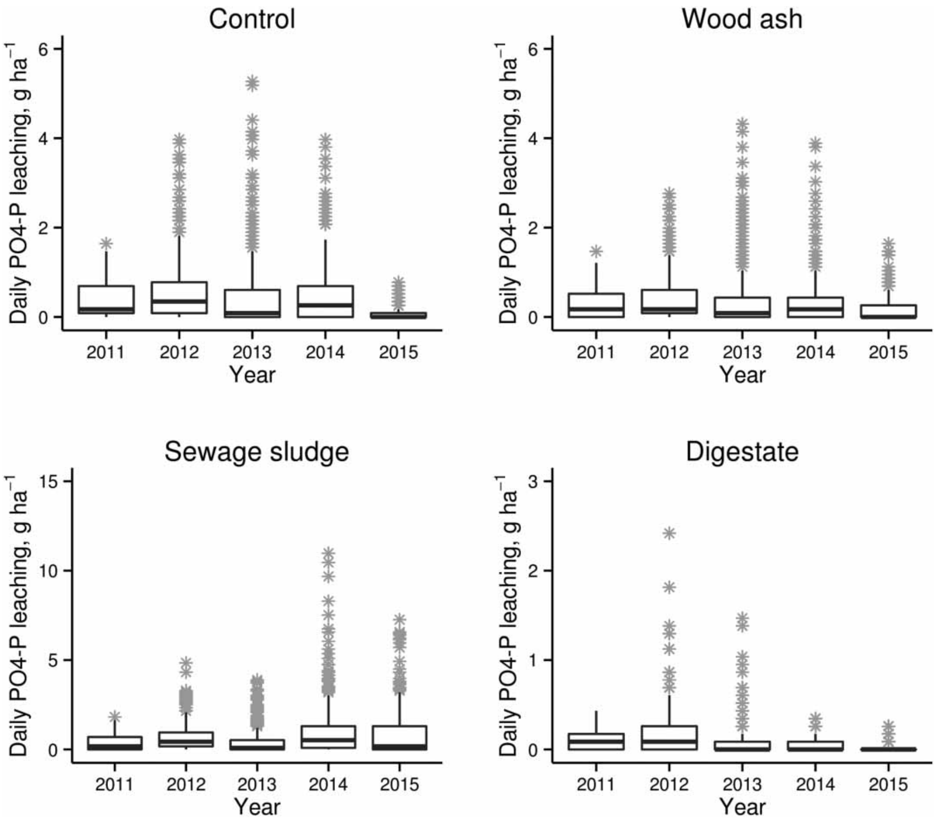

Figure 5 | Daily mean phosphate-phosphorus leaching from the study area during 2011–2015. In the boxplots, the median is shown by the bold line, the box corresponds to lower and upper quartile, whiskers show minimum and maximum values (within 150% of interquartile range from the median) and grey stars represent outliers of the datasets.

and liming, method and rate of K application, and K absorption by plants. The fate of the nutrient K has received less attention than that of nitrogen or phosphorus, because K is not usually considered an environmental pollutant and its leaching does not result directly in eutrophication, but K leaching from soil may affect plant growth and quality (Broschat 1995; Kolahchi & Jalali 2007). Daily mean K leaching from the study area during 2011–2015 is presented in Figure 6. Amounts of K leached per day varied considerably in response to the fertilizer used and meteorological conditions. The highest daily K leaching from the study area was observed in 2012 (one year after application of fertilizer) in the plots fertilized with wood ash – the amount of K leached per day increased to a maximum of 485.4 g K ha^{-1} d^{-1} in 2012, but from 2013 to 2015 it remained relatively constant at average 25.4 to 41.8 g ha^{-1} d^{-1}. In control plots, K leached per day decreased from average 32.3 g ha^{-1} d^{-1} in 2011 to 8.6 g ha^{-1} d^{-1} in 2015. Also, the annual average K leaching generally declined over time for all treatments to a minimum of 3.12 kg K ha^{-1} yr^{-1} in control plots in 2015 (Table 5). Despite the downward trend of annual K leaching, even in unfertilized plots the K leaching exceeded K input via atmospheric deposition, reflecting the mineralization process of potassium-containing minerals.

CONCLUSIONS

The results from the analysis of the five years' trends of macronutrient concentrations in soil solution and amounts of nutrients leached in fertilized juvenile hybrid aspen (*P. tremuloides* × *P. tremula*) plantation cultivated in an agroforestry system in hemi-boreal conditions can be summarized as follows:

(1) Amounts of macronutrients leached per day varied considerably, but annual macronutrient leaching generally

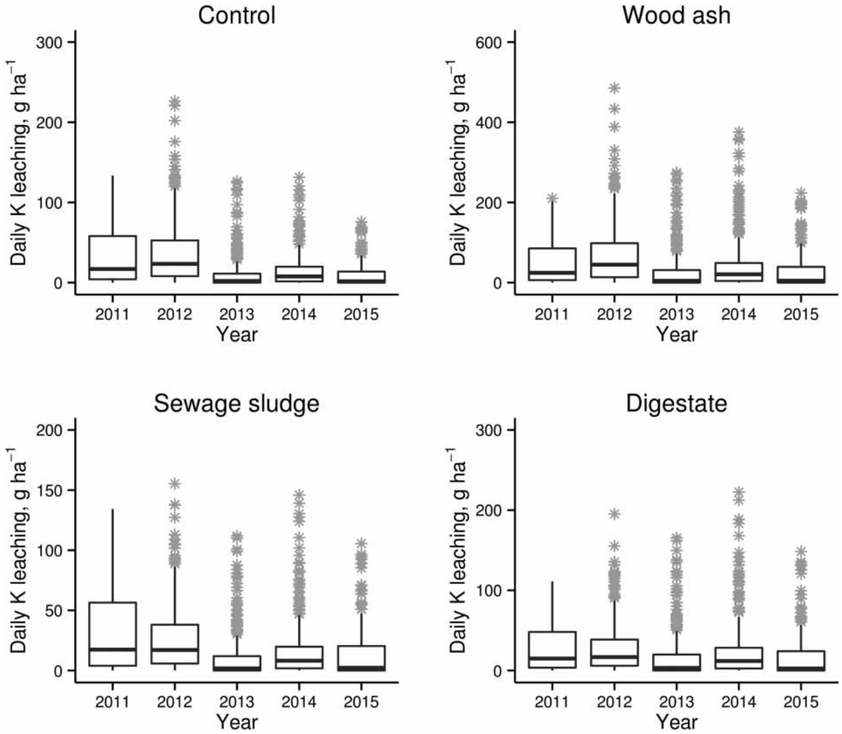

Figure 6 | Daily mean potassium leaching from the study area during 2011–2015. In the boxplots, the median is shown by the bold line, the box corresponds to lower and upper quartile, whiskers show minimum and maximum values (within 150% of interquartile range from the median) and grey stars represent outliers of the datasets.

decreased over time after establishment of the plantation in agricultural land in response not only to meteorological conditions, but also to type of fertilizer used. In the third year after the establishment of the plantation and application of fertilizers, NO_3^--N input via atmospheric deposition exceeded NO_3^--N leaching despite the initial input of total N up to 259 kg ha^{-1} via application of fertilizers, pointing to the intensive NO_3^--N cycling in the agroforestry ecosystem and effective uptake of the excess NO_3^--N by roots of the trees and other plants present.

(2) Juvenile hybrid aspen plantations cultivated in agroforestry systems help mitigate leaching of macronutrients from agricultural lands in the Baltic Sea region. Despite the additional input of macronutrients via the application of fertilizers, during the five-year period after establishment of a hybrid aspen plantation in agricultural land, nitrate leaching decreased up to 99.6%, phosphate leaching decreased up to 97.1%, but potassium leaching decreased up to 76.5%.

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