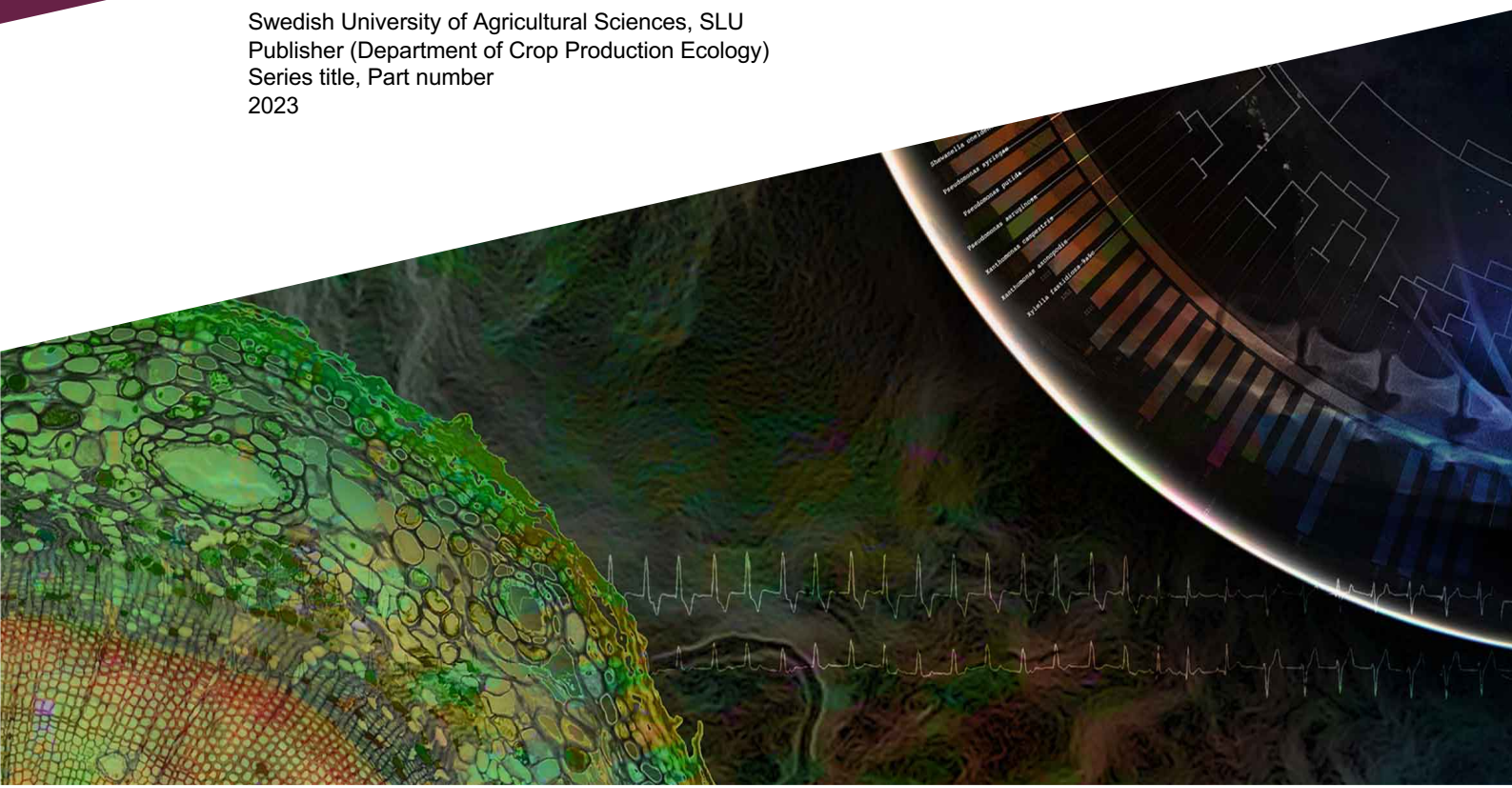
Fertilization of poplar plantations with dried sludge

A demonstration trial in central Sweden

Anneli Adler & Almir Karacic

Swedish University of Agricultural Sciences, SLU
Publisher (Department of Crop Production Ecology)
Series title, Part number
2023



Fertilization of poplar plantations with dried sludge. A demonstration trial in Central Sweden

Anneli Adler, https://orcid.org/0000-0001-7525-1224, Swedish University of Agricultural Sciences, Department of Crop Production Ecology, Uppsala, Sweden
Almir Karacic, https://orcid.org/0000-0002-0180-812X, Swedish University of Agricultural Sciences, Department of Crop Production Ecology, Uppsala, Sweden

Editor:	Editor's name, university, department (if any)
Publisher:	Swedish University of Agricultural Sciences, Faculty of Natural Resources and Agricultural Sciences, Department of Crop Production Ecology
Year of publication:	**2023**
Place of publication:	**Uppsala**
Copyright:	All featured images are used with permission from the copyright owner.
Title of series:	Department of Crop Production Ecology / Reports from the department
Part number:	Report No. 35
ISSN :	1653-5375
ISBN (tryckt version):	978-91-8046-671-4
ISBN (elektronisk version):	978-91-8046-672-1
DOI:	https://doi.org/10.54612/a.2q9iahfphk
Keywords:	nutrients recycling, wastes, woody biomass production, fertilization, poplar, *Populus*, sewage sludge, limiting values, heavy metals, phosphorus

© 2023 (SLU)
Printer: SLU Grafisk Service, 750 07 Uppsala, Sverige

Abstract

Wastewater sludge contains essential nutrients for plant growth and is frequently used as fertilizer in European agriculture. Sludge also contains high concentrations of heavy metals, microplastics, and other substances potentially harmful to human health and the environment. Dried sludge is a product suitable for fertilization of short-rotation poplar plantations in a circular model, recycling nutrients, and turning waste into a resource for increased biomass production. In Hillebola, central Sweden, we demonstrated the application of dried sludge to pilot plantations of climate-adapted *Populus trichocarpa* clones. The trial was established in four blocks with four treatments: NPK fertilizer + cultivation, sewage sludge + cultivation, non-fertilized + cultivation, and control (no treatment). We also sampled ground vegetation at the end of the first growing season and analyzed poplar foliage N and C content. The effect of fertilization on poplar growth was evaluated after two growing seasons, showing a significantly improved basal area increment in NPK and sludge treatments compared to the control. In the spring of 2021, blocks 3 and 4 were extensively damaged by a vole population outbreak, and the damage was more severe in the fertilized plots. The ground vegetation inventory revealed substantial differences in weed biomass between control and cultivated plots. However, the quantified weed occurrence was not used in the mixed model as an explanatory variable for poplar growth because the resulting model was difficult to interpret. Control plots contained double the amount of aboveground grass and herbaceous biomass (8.6 ton ha^{-1}) compared to cultivated and cultivated + fertilized plots. We attributed the improved basal area increment to fertilizers rather than cultivation. The low-intensity Nordic-Baltic poplar establishment practices allow for a substantial amount of ground vegetation to develop until the canopy closure, potentially contributing to the soil carbon pool more than it is usually recognized when modeling carbon balances in short-rotation poplar plantations.

Keywords: carbon balance, fertilization, poplar, *Populus*, sewage sludge.

Table of contents

1. Background **6**
2. Materials and methods **8**
2.1 Site description 8
2.2 Trial Design and Treatments 9
2.3 Sludge Drying and Chemical Properties 11
2.4 Measurements and Sampling 14
2.4.1 Poplar Growth and Biomass 14
2.4.2 Ground Vegetation 14
2.4.3 Foliage Carbon and Nitrogen 15
2.4.4 Damage 15
2.5 Statistical Analysis 15
3. Results and Discussion **16**
4. Conclusions and Practical Recommendations **20**
References **20**
Acknowledgments **22**

1. Background

Municipal sewage sludge is waste containing essential nutrients for plant growth, such as nitrogen (N), phosphorus (P), potassium (K), and carbon (C). It also contains heavy metals such as Cd, Cu, Hg, Ni, Pb, Zn, microplastics, pathogens, antibiotics, polyfluorinated hydrocarbons (PAF), and other substances that can threaten health and the environment. Despite the potential risks, approximately 50% of all European municipal sewage sludge is utilized to fertilize agricultural and energy crops. In Sweden, however, approximately 35% out of 200,000 dry-weight tons annually produced municipal sewage sludge is used as fertilizer (SOU, 2020:3). The risks versus benefits of sludge fertilization in agriculture have been lively debated among different stakeholders since Sweden joined the EU Directive 86/278/EEC on the protection of the environment and soil (Ekane et al., 2021). Starting in 2008, an increasing number of Swedish stakeholders have joined the REVAQ initiative for a voluntary sludge certification system aiming to minimize the risks of sludge fertilization.

The REVAQ certification framework establishes quality requirements, working on upstream source separation and transparency along the entire sludge production cycle and its application to the agricultural field. Today, more than 80% of sludge being spread on Swedish arable fields is REVAQ certified, and the system has managed to continuously reduce microbial and heavy metal content, particularly the concentrations of Cd. Despite REVAQ improvements and evidence from long-term trials for no heavy-metal accumulation in crops or alarming levels in soils, a substantial cautiousness is constantly present regarding the potential risks of introducing toxic and environmentally harmful substances into the food chain.

The current national regulatory framework (SNFS 1994:2, SNFS 1998:4, and 2001:5) has been under revision, resulting in SOU 2020:3, whose inquiry was to formulate the proposal for banning the disposal of sewage sludge on agricultural land. However, the recommendations specified in SOU 2020:3 suggest a more stringent regulatory framework rather than a total ban on spreading municipal sewage sludge on arable land.

Long-lasting Swedish trials with annual sludge application of 1-3 tons per hectare have been running since the 1980s, showing no signs of heavy metals or other contaminants accumulation in harvested crops (Martinsson, 2020) and only minor accumulation in the soil (Kirchman et al., 2017). At the same time, there was an increase in organic soil carbon of up to 17 tons per hectare within the top 40 cm soil layer (Börjesson & Kätterer, 2018). The registered soil carbon accumulation in the trial was suggested to be the main factor behind the positive effects on crop yields (Kätterer et al., 2014; Kirchmann et al., 2017).

The disposal of municipal sewage sludge in short-rotation energy crops with fast-growing species like poplars and willows has been discussed in Sweden since these crops started to be cultivated in the 1980s. The system was particularly thoroughly studied in willow coppice and regarded to be efficient

in removing Cd and other heavy metals from the soil (Adler et al., 2008; Labrecque et al., 1997 and 1998; Hasselgren, 1998; Ladzina et al., 2007). Internationally, extensive research has been conducted on using short-rotation crops in waste-management systems, reporting mainly positive effects on biomass production and the build-up of carbon in topsoil (Marron, 2015). Most studies were conducted on poplar and willow coppice in short cutting cycles.

Transport is the most significant single cost in wet sludge treatment and disposal, and reducing these costs has been a focus for the system developers since sludge spreading in crops became a viable recycling alternative (Ridell-Black, 1994). In recent decades, many wastewater treatment plants (WWTPs) have been drying sludge digestate to improve its combustion properties. Dried sludge is also cheaper to transport and is easily spread in agricultural fields using conventional granular fertilizer spreaders. Moreover, the content of easily soluble nitrogen (NO_3^- and NH_4^+) and phosphorus (P_2O_5) is small (0.2% and 0.1% of the dry content), which reduces the eutrophication risk. Most of N (around 4% of the dry content) is in organic form, slowly mineralizing over several years (Hall, 1986).

This report presents the work on the demonstration trial in Hillebola, central Sweden. The trial was a part of the "NutriBiomass4LIFE" project (LIFE17/ENV/LV000310), co-financed by the Swedish Energy Agency (P-45082-1). The project's main goal was to develop and demonstrate a full-scale circular economic model for sewage sludge nutrient recycling in fast-growing poplar plantations. Pelleted sewage sludge used for fertilization of poplar plantations in Lithuania was produced in Vilnius WWTP through thermal hydrolysis, a highly efficient sludge treatment technology that increases the digestate dry content from 30% to 90%, resulting in a pasteurized, pathogen- and stench-free product suitable for spreading on arable land. This recycling model represents a closed-loop, sustainable sewage sludge handling, providing an environmentally friendly, long-term solution for sludge disposal. It enables phosphorus and nitrogen recycling while improving biomass yields and soil carbon storage. The improved yields increase the biomass assets for energy and diverse industrial sectors. Poplar biomass can be used for heat and electricity production, liquid fuels, dissolving pulp for textiles, and other, more long-lived products like structural or interior fiber boards and furniture (Fig. 1).

The primary goal of the Hillebola trial was to demonstrate the opportunities for sludge disposal in the operative poplar plantations in Sweden.

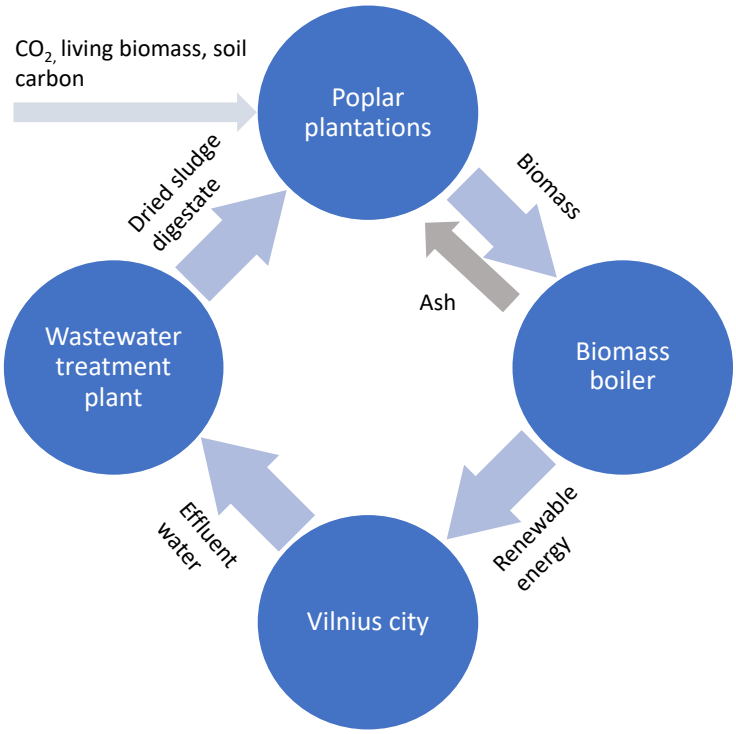


Figure 1. The closed-loop circular economy model of nutrient-rich waste recycling tested in Vilnius, Lithuania, developed within the 'NutriBiomass4LIFE' project.

2. Materials and methods

2.1 Site description

The poplar plantation is located in the coniferous-dominated landscape outside Hillebola, central Sweden (block 1 - 60.351975 N, 17.690794 E; block 3 - 60.349752 N, 17.667424 E). The area of set-aside arable land, approximately 25-30 hectares, was planted in 2016 with climate-adapted *Populus trichocarpa* clones. The parcel with blocks 1 and 2 was previously grown with food and fodder crops, while blocks 3 and 4 were established on grassland (Fig 2).

Block 1 was established on a mild slope, whereas all other blocks were placed low in the terrain. In the past, both fields were ditched along the lowest isohypses to improve water drainage. The texture in 30 cm topsoil differed among the blocks, ranging from clay loam to loamy sand. The soil in blocks 1 and 2 can be considered more fertile. It also contained higher concentrations of almost all heavy metals than light-textured soil in blocks 3 and 4 (Tables 2 and 3).

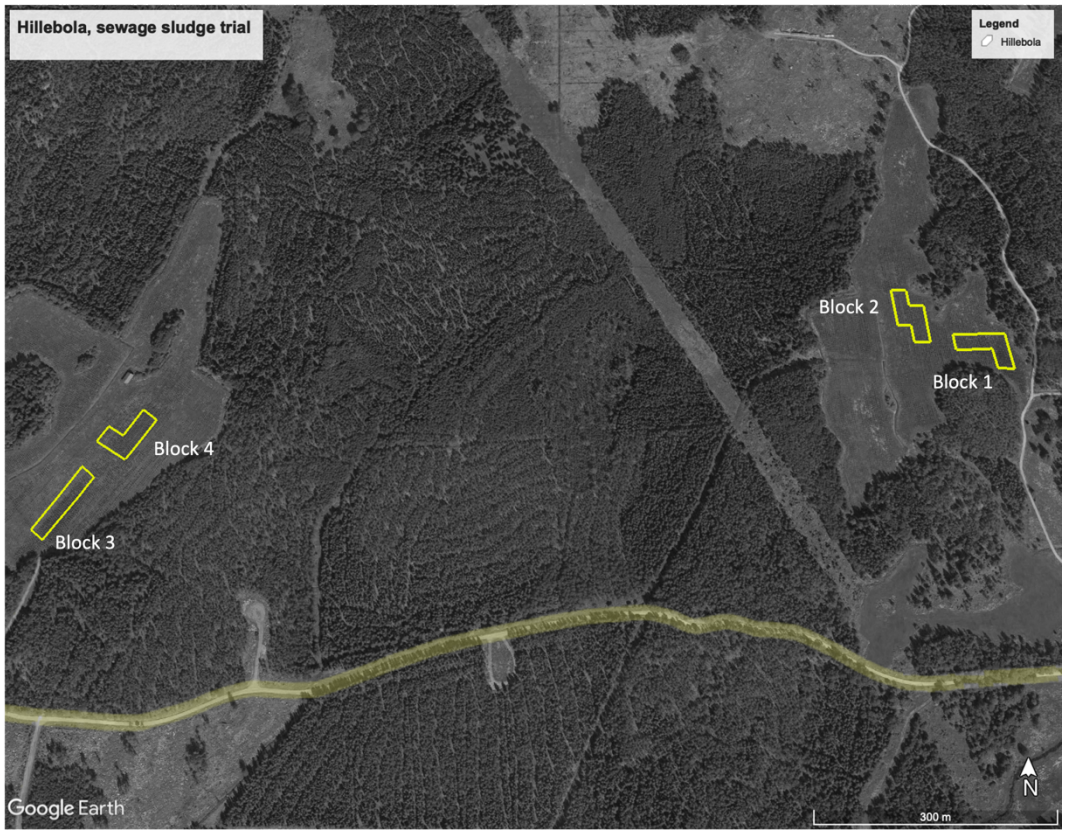


Figure 2. The four blocks of the Hillebola trial are placed on two nearby fields. The soil characteristics and previous land use of these two fields were different.

The plantation was established by planting bare-root plants of black cottonwood clone mixture bred at the Swedish University of Agricultural Sciences (Karacic et al., 2021; Adler et al., 2021; Richards et al., 2020; Vicko et al., 2021). Established was successful, and early growth was satisfactory despite a lack of weed management. At the end of the third growing season, the average DBH and tree height were 17 mm and 2.5 m, respectively (Figures 3 and 4). Planting density ranged between 1,281 and 1,706 trees per hectare, corresponding to a spacing range of approximately 2.5×2.65 to 2.5×2.9 m. The row spacing was too narrow to enable entering the plantation with commercial granular spreaders. In the random treatment application, the initial planting densities still varied between the treatments, with the lowest average density in control plots (1,381 trees ha^{-1}) and the highest in the NPK plots (1,520 trees ha^{-1}). We tried to account for these differences in the statistical analysis by including the initial plot basal area as a covariate.

2.2 Trial Design and Treatments

The treatments were applied to 25 × 25 = 625 m^2 large plots, whereas the growth estimates were made on net plots of an approximate size of 15 × 15 = 225 m^2. The spacing of a plot was estimated on the net plot. Four treatments were applied: i) NPK conventional fertilizer + soil cultivation, ii) sewage sludge + soil cultivation, iii) soil cultivation only, and iv) control, i.e., no fertilizer or soil cultivation. A

small shallow plow was used for the cultivation treatment and to mix NPK and sludge into the soil as other implements, such as a rotary cultivator, could not fit between the tree rows. NPK was spread manually, whereas a sand spreader was used to apply sewage sludge between plot rows (Fig. 5).



Figure 3. A view over the location of block 1 in May 2019, one month before the treatment application.



Figure 4. View over the location of block 3 in May 2019, one month before the treatment application.



Figure 5. Left: Treatments were applied at the beginning of June using a small tractor that could fit between the densely planted poplar rows in Hillebola. Right: A shallow plow of ca 10 cm depth was used to simulate soil cultivation between the tree rows.

2.3 Sludge Drying and Chemical Properties

Dried sludge was obtained from Moravatten AB in Orsa and spread immediately after transporting it to the trial. The drying process contained centrifugation of sludge with 23-25% DW and feeding it from a silo to a large slow, tightly masked tape in the dryer. The temperature in the dryer was about 160°C, and the residence time on the belt was about one hour, 30 min on the upper belt and under hot air, and 30 min on a lower belt with cold air circulation. The delivered sludge contained 90% of the dry matter and was not REVAQ certified (Fig 6, Table 1).

The soil belonged to the third (blocks 1 and 2) and fifth (blocks 3 and 4) P-class. Thus, the P-class five limits were adopted with a maximum allowance of 160 kg P ha^{-1} over seven years (SNFS 1004:2). In our case, the amount of sludge was further limited to 135 kg P ha^{-1} as the Cr content appeared to be the limiting factor (Table 3). After spreading, the sludge was worked into the soil.



Figure 6. Dried sludge was delivered at the beginning of June from Moravatten AB. The sludge was spread the same day.

Table 1. Extract from the sludge analysis from MoraVatten AB used for fertilization in the Hillebola trial. The limiting values for heavy metals in sludge to be used as fertilizer are provided in parenthesis.

Sludge characteristics	Heavy metals in mg/kg
Dry substance	90%
pH	6.9
Organic C	43,80%
N-total	3,25%
NH_4-N	1%
P-total	1.50%
Cu	150,00 (600)
Pb	9,00 (100)
Zn	360.00 (800)
Ni	12.00 (50)
Cr	31.00 (100)
Cd	0.50 (2)
Hg	0.30 (2.5)

Table 2. Soil chemistry and texture per block in Hillebola before the treatment application. Block 1 – loam, Block 2 – clay loam, Block 3 – loamy sand, and Block 4 – sandy loam.

Block	pH	P-AL	K	Mg	K	Ca	Al	Fe	NO_3 NO_2-N	Humus	Clay	Silt	Sand
		mg/100g	mg/100g	mg/100g		mg/100g	mg/100g	mg/100g	mg/100g	%	%	%	%
1	6.2	22.3	23.0	12.4	1.9	243	28	76	0.8	4.5	20	34	42
2	7.4	18.4	16.4	14.8	1.1	644	17	57	1.0	5.4	27	45	23
3	5.6	6.1	2.9	3.1	0.9	60	32	81	0.2	3.6	< 4	16	76
4	6.0	4.4	5.0	11.3	0.4	214	18	118	0.4	5.2	11	32	51

Table 3. Soil heavy metal content for the two fields in Hillebola before the treatment with sewage sludge (mg/kg DW)

Block	As	Ba	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
1-2	4.28	101	0.312	9.83	27.3	33.4	<0,2	21.9	19.0	35.2	89.5
3-4	2.33	109	0.135	2.57	9.11	9.70	<0,2	6.90	8.67	16.0	25.9

Table 3. The amount of applied sludge was based on the limiting amounts of added P and heavy metals.

Sludge chemical elements	Calculated dosage of dried sludge based on SNFS 1994:2 (limiting values in parenteses)
	kg ha^{-1} 7 $years^{-1}$
Sludge, total weight	10,036
Sludge, dry weight	9,032
P-total	135
N-total	294
C-organic	3,956
	g ha^{-1} $year^{-1}$
Cu	193.55 (300)
Pb	11.61 (25)
Zn	464.52 (600)
Ni	15.48 (25)
Cr	**40 (40)**
Cd	0.65 (0.75)
Hg	0.39 (1.5)

2.4 Measurements and Sampling

2.4.1 Poplar Growth and Biomass

DBH and height were measured on 36 trees (6×6) on each net plot. Provided the differences in spacing among the plots, the exact area of net plots was measured and used to calculate the planting density and basal area (BA) per hectare in each plot. The measurements were performed in May 2019 and two growing seasons later, in spring 2021.

In August 2019, the total biomass of eight poplar trees was sampled, and the resulting data were used to construct the growth model and estimate the initial leaf area index. However, this data was not used to evaluate treatment effects as the plot basal area (BA) is a directly assessable parameter.

2.4.2 Ground Vegetation

The aboveground biomass of ground vegetation was sampled at the beginning of September 2019. Four sampling plots per block and treatment, 64 plots in total, were laid systematically to obtain a representative sample of the ground vegetation cover. The plot size was $0.5 \times 0.5 = 0.25$ m^2. Three out of four plots were positioned between rows to cover the vegetation occurrence of the cultivated area in the plots. The same positioning pattern, three between one within the rows, was also applied in control plots. The within-row area represented 25% of the plot area and was consequently sampled with one representative sample per treatment and block.

The aboveground part of ground vegetation within the 0.25 m^2 sample plots was cut, dried to a constant weight at 95°C, and weighed. The biomass from sample plots was then upscaled to an area unit of one hectare (Fig 7).



Figure 7. A typical grass (left) and herbaceous (right) plot at the poplar plantation in Hillebola sampled at the beginning of September 2019. The herbaceous vegetation occurred mostly on cultivated soil between the poplar rows, had less biomass, and posed less severe competition to poplar trees.

2.4.3 Foliage Carbon and Nitrogen

The foliage carbon and nitrogen were analyzed on leaves sampled in the autumn of 2020. The samples were gathered systematically, one leaf per tree at a two-meter height from 2/3 of the branch length oriented to the east, i.e., towards the area between rows oriented in a south-north direction.

2.4.4 Damage

The poplar plantation in Hillebola was not fenced, and some moos damage occurred in the net plots. These damages were not systematically inventoried, and even if they were, it would not be easy to produce a reasonable quantitative estimate of their impact on basal area increment (BAI). The most common damage was breakage or bending of the top shoot. In most cases, the damaged trees recovered by developing another top shoot.

In spring 2021, several plots in blocks 3 and 4 were damaged by voles. A high vole population seems to have developed over the whole location, but particularly heavy damage was noticed in fertilized plots. The trees were ring-barked and died in 2021 and 2022, which hindered the follow-up estimates of growth performance.

2.5 Statistical Analysis

We used ANCOVA to evaluate the effects of fertilization treatments on poplar growth. The plot basal area increment (BAI), i.e., the increment of the cross-sectional area at 1.3 m height of all the trees on a plot, has been used as the

growth parameter because of its direct relationship to biomass estimates and its direct assessment from the measurements of DBH. BA per plot before treatment application was used as covariance. Block was assigned as a random variable.

Ground vegetation biomass was analyzed with two-way ANOVA using the four treatments and four blocks as factors. We also examined the variation of estimated herbaceous and grass cover within different treatments.

3. Results and Discussion

Basal area increment (BAI) was significantly and positively affected by fertilization treatments and the initial BA (Table 4 and 5, Fig 8). The BAI was significantly higher in NPK and sludge treatment than in the control but not cultivation treatment without fertilizer application (Table 5). The positive effect of NPK treatment was expected due to a high dosage of mineral nitrogen (294 kg). However, the same increase in BAI was also achieved with sludge treatment, though only 25% of the sludge nitrogen was in ammonium form (NH_4-N), the rest being bound in organic compounds (Table 1). Both NPK and sludge treatments had a higher BAI compared to cultivated, non-fertilized plots, even if the significance of these differences could not be statistically confirmed within the actual trial design.

Table 4. The ANCOVA table for the analysis of logarithm-transformed basal area increment (lnBAI) as dependent on block and treatment. The initial basal area (LnBA18) was introduced as covariance to compensate for the effect of tree size (initial DBH) on growth in 2020 and 2021.

Cases	Sum of Squares	df	Mean Square	F	p
Block	0.278	3	0.093	5.452	0.025
Treat	0.513	3	0.171	10.059	0.004
BA18ha(m2)	0.227	1	0.227	13.333	0.006
Residuals	0.136	8	0.017		

Fertilization is an essential measure of yield improvement in operational willow short-rotation coppice (Aronsson et al., 2014). Hansen et al. (1988) and Hansen (1994) recommended early fertilization of densely planted poplars in the years before canopy closure. After that, nutrient cycling retains the increased N-concentrations within the poplar canopy. Several other studies also reported positive fertilization effects in poplar plantations (Heilman and Xie, 1993; Coleman et al., 2006). However, limited or no effects were recorded in other studies (van den Driescche et al., 2005; DeRochers et al., 2007). In a Swedish study, Dimitriou and Mola-Yudego (2017) concluded that fertilization in younger but not in older poplar plantations positively affected DBH development. However, the effects were estimated not to exceed 6% in the biomass production increase.

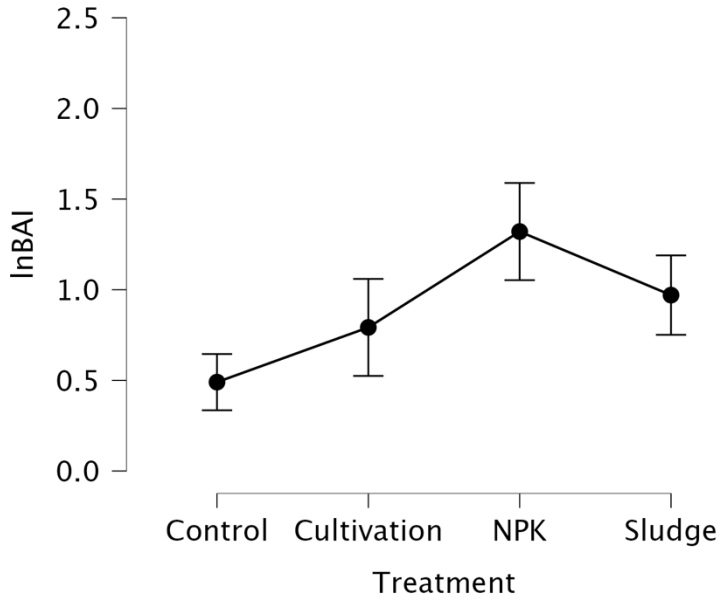


Figure 8. The effects of fertilization and cultivation treatments on the basal area increment (BAI) two growing seasons after the treatment application. Slam+Cult = sludge + cultivation.

Table 5. Pairwise comparisons of basal area increment (lnBAI) between the fertilization/cultivation treatments in Hillebola.

		Mean Difference	SE	t	p_{tukey}
Control	Cultivation	-0.194	0.097	-2.007	0.262
	NPK	-0.522	0.125	-4.171	0.013 *
	Sludge	-0.439	0.093	-4.725	0.006 **
Cultivation	NPK	-0.328	0.107	-3.050	0.062
	Sludge	-0.245	0.094	-2.603	0.116
NPK	Sludge	0.083	0.118	0.704	0.893

There is uncertainty regarding the long-term effect of fertilization in poplar plantations, and we cannot say if NPK and sewage sludge would differ in this respect. However, the analyzed leaf samples showed increased nitrogen concentrations in trees growing on fertilized plots, thus also suggesting the increased BAI to be the direct effect of additional nutrient uptake (Fig 9). As poplar trees are very efficient in recycling nitrogen within the system, it can be expected that these increased nitrogen levels will contribute to permanently increased yields. The levels of leaf-N in control and cultivation treatments suggest a moderate nitrogen deficiency (Hansen, 1994).

Ground vegetation contributed significantly to the biomass pool at the end of 2019, particularly in control plots (Fig. 10). In these plots, the aboveground biomass of grasses and herbs was twice as high as in cultivated and fertilized plots, reaching almost an average of nine tonnes per hectare. However, the ground vegetation is quickly outcompeted by the closing poplar canopy. In the NPK treatment in block 1, for example, the ground was completely free from the vegetation in 2022, three years after our sampling, when the aboveground ground vegetation weighed 4.1 tons ha^{-1} (Fig. 11).

Ground vegetation inhibits poplar growth, evident in our trial from the higher BAI in cultivated non-fertilized plots compared to control plots. Mechanical weed control is therefore always recommended as a necessary maintenance measure in the plantation establishment phase. However, in the case of the Hillebola plantation and other operative plantations in Sweden established by farmers and forest companies, weed management is deprioritized to keep the establishment costs low. The initial herbicide treatment and soil preparation are sufficient when combined with more robust planting material, usually bare-root plants. At the same time, a somewhat prolonged establishment phase and rotation are accepted. In Hillebola, the soil scarification in cultivation-only plots is carried through at the beginning of the fourth year. Until then, all treated plots, control and cultivation-only, had the same development and were established reasonably well. The measured difference in BAI between cultivation-only and control would likely be more significant if the cultivation was applied annually from year one and even repeated a couple of times within each of the first three growing seasons. However, Hillebola is a wind-shielded site with fertile, mostly well-aerated soil, and the establishment was successful anyway. In contrast, the omission of weed control on sites with some inherent limiting factors can result in establishment failure or the formation of production-lowering gaps in a stand.

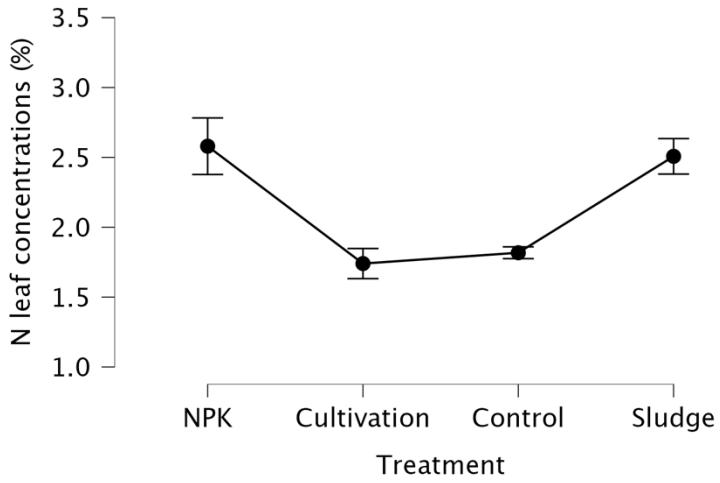


Figure 9. The concentration of nitrogen (%) in leaves of trees grown in Hillebola at the end of the first growing season after applying treatments.

When modeling nutrient and carbon budgets in poplar plantations, ground vegetation is usually neglected (i.e., Ericsson et al., 2013). Our estimates at the end of the fourth growing season (Fig 10) show that substantial amounts of biomass (8.6 tons ha^{-1} aboveground biomass in the control treatment) are allocated to ground vegetation and turned over annually. The contribution of this carbon pool to the build-up of soil carbon (SOC) in poplar plantations can be underestimated in the existing models.

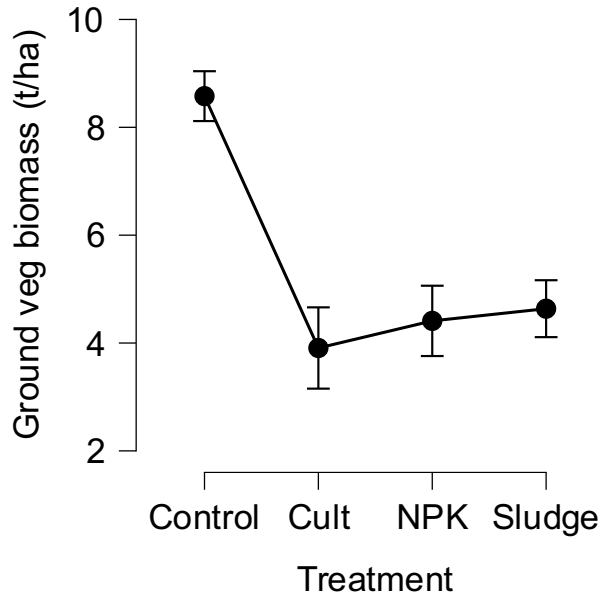


Figure 10. The ground vegetation biomass (ton ha-^{1}) in different treatments.



Figure 11. NPK treatment in block one, summer 2023, four years after the inventory of ground vegetation estimating its aboveground biomass to 4.1 ton ha^{-1}. (analysis presented in Figure XX). Already in 2022, canopy closure eliminated the ground vegetation layer. As the canopy closes, additional nutrients become available to poplars by mineralizing nutrients bound in ground vegetation.

4. Conclusions and Practical Recommendations

Despite its limited scope, the Hillebola trial demonstrated the potentially positive effects on biomass production in poplar plantations. This demonstration did not include a follow-up on the soil concentration of potentially hazardous substances or nutrient leakage. These aspects of sludge spreading in poplar plantations were evaluated in the Lithuanian large-scale operative part of NutriBiomass4LIFE.

The Hillebola demonstration trial provided the following insights:

1. Sludge spreading in young poplar plantations 2-4 years before canopy closure positively affects tree growth.
2. There is a substantial amount of ground vegetation cover in the young poplar plantations, contributing to the soil carbon pool. A portion of nutrients applied with sludge is also captured by ground vegetation. The nutrients released through subsequent mineralization of this biomass pool will likely be an additional nutrient source to a closing canopy of young poplar stands.
3. We suggest only light soil cultivation when spreading sludge in well-established poplar plantations, enabling the ground vegetation to recover quickly, helping to capture excessive nutrients, and decreasing the risks of nutrient leakage.
4. The efficient sludge spreading in poplar plantations requires spacings with at least 3.3 m between the rows.

References

Aronsson, P., Rosenquist, H. and Dimitriou, I. (2014). Impact of nitrogen fertilization to short-rotation willow coppice plantations grown in Sweden on yield and economy. Bioenergy Research 7, 993 – 1001. DOI 10.1007/s12155-014-9435-7.

Börjesson G & Kätterer, T. (2018). Soil fertility effects of repeated application of sewage sludge in two 30-year-old field experiments. Nutr Cycl Agroecosyst (2018) 112:369–385 https://doi.org/10.1007/s10705-018-9952-4

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

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. and Mila-Yudego, B. (2017). Nitrogen fertilization of poplar plantations on agricultural land: effects on diameter increments and leaching. Scandinavian Journal of Forest Research, Volume 32:8, 700-707, DOI:10.1080/02827581.2016.1264622

Ekane, N. Barquet, K., and Rosemarin, A. (2021). Resources and Risks: Perceptions on the Application of Sewage Sludge on Agricultural Land in Sweden, a Case Study. Front. Sustain. Food Syst. 5:647780. doi: 10.3389/fsufs.2021.647780

Ericsson, N., Porsö, C., Ahlgren, S., Nordberg, Å., Sundberg, C. and Hansson, P-A. (2013). Time-dependent climate impact of a bioenergy system – methodology development and application to Swedish conditions. GCB Bioenergy (2013) 5, 580–590, doi: 10.1111/gcbb.12031.

Hall, J.E. (1986). The Agricultural Value of Sewage Sludge. WRc Report No ER 1220-M. WRc Medmenham, Marlow.

Hansen, E.A, McLaughlin, R.A. & Pope, P.E. (1988). Biomass and nitrogen dynamics of hybrid poplar on two different soils: implication for fertilization strategy. Canadian Journal of Forest Research 18(2): 223-230.

Hansen, E.A. (1994). A guide for determining when to fertilize poplar plantations. United States Department of Agriculture, North Central Forest Experiment Station, Research paper NC-319, St. Paul, Minnesota, 7 pp.

Heilman, P. E. and Xie, F-G., 1993. Influence of nitrogen on growth and productivity of short-rotation *Populus trichocarpa x Populus deltoides* hybrids. Canadian Journal of Forest Research 23, 1863-1869.

Kätterer T, Börjesson G, Kirchmann, H (2014) Changes in organic carbon in topsoil and subsoil and microbial community composition caused by repeated additions of organic amendments and N fertilization in a long-term field experiment in Sweden. Agric Ecosys Environ 189:110–118. https://doi.org/10.1016/j.agee.2014.03.025

Kirchmann H, Bo¨rjesson G, Ka¨tterer T, Cohen Y (2017) From agricultural use of sewage sludge to nutrient extraction: a soil science outlook. Ambio 46:143–154. https://doi.org/10.1007/s13280-016-0816-3

Marron, N. (2015). Agronomic and environmental effects of land application of residues in short-rotation tree plantations: A literature review. Biomass & Bioenergy, Volume 81, October 2015, Pages 378-400. https://doi.org/10.1016/j.biombioe.2015.07.025

Martinsson, U.D. (2020). Slamtillförsel på åkermark: Slamrapport 2015-2018. Hushållningssällskapet.

Ridell-Black, D. (1994). Sewage sludge as a fertilizer for short-rotation energy coppice. In: Willow vegetation filters for municipal wastewaters and sludges – A biological purification system. Proceedings of a study tour, conference and workshop in Sweden, 5-10 June 1994. Ed: Aronsson, P & Perttu, K. Swedish University of Agricultural Sciences, Department of Ecology and Environmental Research, Section of Short Rotation Forestry, Uppsala, Report 50. ISSN 0282-6267. ISBN 91-576-4916-2.

SOU (2020:3). Hållbar slamhantering. Betänkande av Utredningen om en giftfri ochcirkulär återföring av fosfor från avloppsslam. Stockholm.

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

Acknowledgments

The study was financed through the EU LIFE project “NutriBiomass4LIFE” (LIFE17/ENV/LV000310), which was awarded a subsidy from the EU LIFE program, the EU’s funding instrument for environment and climate action and co-financed by the Swedish Energy Agency (P-45082-1) and Ministry of Environment of the Republic of Lithuania.

The sole responsibility for the content of this publication lies with the authors. The European Commission and other funding authorities are not responsible for any use that may be made of the information contained therein.