# Fertilization of poplar plantations with dried sludge

## A demonstration trial in Hillebola - central Sweden

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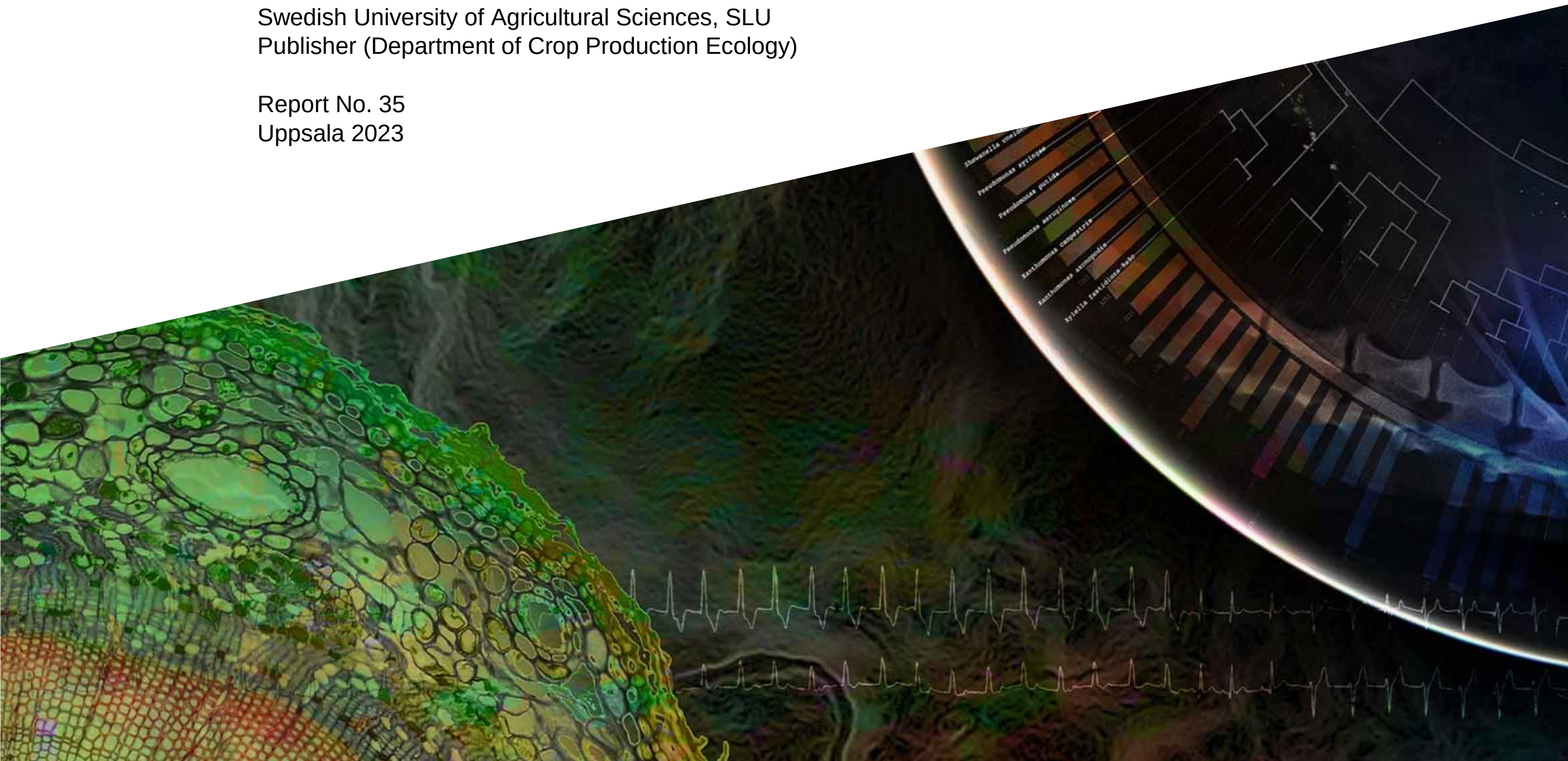

Fertilization of poplar plantations with dried sludge.
A demonstration trial in Hillebola - central Sweden

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## Summary

Wastewater sludge contains essential nutrients for plant growth and is frequently used as fertilizer in European agriculture. Sludge contains elevated concentrations of heavy metals, microplastics, and other substances that may pose potential risks to human health and the environment. Nevertheless, dried pelletized sludge emerges as a viable product for fertilizing short-rotation poplar plantations within a circular model, enabling nutrient recycling and converting waste into a valuable resource to enhance biomass production for different markets. In Hillebola, central Sweden, we demonstrated the application of dried pelletized sludge to pilot plantations with climate-adapted *Populus trichocarpa* clones. The trial was established in four blocks with four treatments three years after the poplar trees were planted. The treatments were: mineral NPK fertilizer + soil cultivation between poplar rows, dried pelletized sludge + soil cultivation, no fertilization + soil cultivation only, and control (no treatments). The effect of fertilization on poplar growth was evaluated two years later, after the fifth growing season. The results showed a significantly improved basal area increment in NPK and sludge treatments compared to the control. The ground vegetation inventory revealed substantial differences in weed biomass between control and cultivated plots. Control plots contained double the amount of aboveground grass and herbaceous biomass (8.6 ton $ha^{-1}$) compared to cultivated and cultivated + fertilized plots. 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, which is the theme of our next report.

## Referat

Avloppsslam innehåller viktiga näringsämnen för tillväxt av jordbruksgrödor och används ofta som gödselmedel inom europeiskt jordbruk. Slam innehåller även förhöjda koncentrationer av tungmetaller, mikroplaster och andra ämnen som kan utgöra potentiella risker för miljön. Trots detta finns möjlighet att använda torkat pelleterat slam som en hållbar produkt för gödsling av kortrotationsskogar på oanvänd mark inom en cirkulär modell, vilket möjliggör näringsåtervinning och omvandlar avfall till en värdefull resurs för att förbättra biomassaproduktionen för olika marknader. I Hillebola, centrala Sverige, demonstrerade vi användningen av torkat pelleterat slam i pilotplanteringar med klimatanpassade kloner av *Populus trichocarpa*. Försöket etablerades i fyra block med fyra behandlingar tre år efter att poppelträden planterades. Effekten av följande behandlingar på trädens tillväxt testades: mineral NPK-gödsel + markbearbetning mellan poppelraderna, torkat pelleterat slam + markbearbetning, ingen gödsling + enbart markbearbetning och kontroll (utan behandlingar). Effekten av gödsling på poppelns tillväxt utvärderades två år senare, efter den femte växtsäsongen. Resultaten visade en signifikant förbättring av grundytetillväxten i NPK- och slambehandlingarna jämfört med kontrollen. Inventeringen av markvegetationen visade betydande skillnader i ogräsbiomassan mellan kontrollbehandlingen och ytorna med markbearbetning. Kontrollytorna innehöll dubbelt så mycket ovanjordisk gräs- och örtbiomassa (8,6 ton/ha) jämfört med gödslade och markbearbetade ytor. De lågintensiva metoderna för poppelodling i den nordisk-baltiska regionen tillåter en betydande mängd markvegetation att utvecklas tills trädkronorna sluter sig, vilket potentiellt bidrar till markens kolinlagring mer än vad som vanligtvis erkänns vid modellering av kolbalanser i kortrotationsskogar med poppel. Detta beskriver vi i vår nästa rapport.

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# 1. Background

Municipal sewage sludge is a waste, containing carbon (C) along with essential nutrients for plant growth, including nitrogen (N), phosphorus (P), potassium (K). It also contains heavy metals such as Cd, Cu, Hg, Ni, Pb, Zn, microplastics, pathogens, antibiotics, polyfluorinated hydrocarbons (PAF), and other substances that pose potential threats to the health of living organisms 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 sets quality standards, focusing on upstream source separation and ensuring transparency throughout the entire sludge production cycle and its application to agricultural fields. Currently, over 80% of the sludge applied to Swedish arable fields is certified under the REVAQ framework. The system has consistently succeeded in reducing microbial and heavy metal content, with notable decreases observed in concentrations of Cd, particularly. Despite improvements under the REVAQ system and evidence from long-term trials indicating no heavy-metal accumulation in crops or alarming levels in soils, there remains a persistent caution regarding the potential risks associated with introducing toxic and environmentally harmful substances into the food chain. The existing national regulatory framework (SNFS 1994:2, SNFS 1998:4, and NFS 2001:5) has undergone revision, as outlined in SOU 2020:3. This revision proposes a formulation for banning the disposal of sewage sludge on agricultural land. However, the recommendations specified in SOU 2020:3 lean towards advocating a more stringent regulatory framework rather than an outright ban on spreading municipal sewage sludge on arable land.

Long-term Swedish trials involving annual sludge application of 1-3 tons per hectare have been ongoing since the 1980s. These trials, as documented by Martinsson (2020), reveal no evidence of heavy metal or contaminant accumulation in harvested crops. Additionally, findings from Kirchman *et al*. (2017) indicate only minor accumulation in the soil. Simultaneously, there was an increase in organic soil carbon of up to 17 tons per hectare within the top 40 cm soil layer after 30 years, as reported by Börjesson & Kätterer (2018). The documented soil carbon accumulation in the trial was proposed to be the primary factor contributing to the positive effects on crop yields, as indicated by Kätterer *et al*. (2014) and Kirchmann *et al*. (2017).

The practice of disposing of municipal sewage sludge in short-rotation woody crops with fast-growing broadleaves, such as poplars and willows, has been under discussion in Sweden since the cultivation of these crops began 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*., 1998; Hasselgren, 1998; Ladzina *et al*., 2007). Internationally, significant research has been carried out on the utilization of short-rotation woody crops in waste-management systems, with findings predominantly highlighting positive impacts on biomass production and carbon accumulation in topsoil (Marron, 2015). The majority of these studies focused on poplar and willow coppice within short cutting cycles.

Transportation stands out as the most substantial individual expense in sewage sludge treatment and disposal, primarily owing to its high water content. Reducing these costs has been a primary focus for system developers ever since sludge spreading in crops emerged as a viable recycling alternative (Ridell-Black, 1994). In recent decades, numerous wastewater treatment plants (WWTPs) have been drying sludge digestate to enhance its combustion properties. Dried sludge is not only more cost-effective to transport but can also be 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, respectively), 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 recycling sewage sludge nutrients in fast-growing poplar plantations. Pelleted sewage sludge utilized for fertilizing poplar plantations in Lithuania was generated at the Vilnius WWTP using thermal hydrolysis. This highly efficient sludge treatment technology elevates the dry matter content of digestate from 30% to 90%, yielding a pasteurized, odor-free product devoid of pathogens, suitable for spreading on arable land. This recycling model represents a closed-loop, sustainable approach to sewage sludge management, offering an environmentally friendly, long-term solution for sludge disposal. It enables P and Nrecycling while improving biomass yields and soil C 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 biofuels, dissolving pulp for textiles, and other, more long-lived products like structural or interior fiber boards and furniture (Figure 1).

The primary goal of the Hillebola trial was to demonstrate the opportunities for sludge disposal in the operative poplar plantations in Sweden. The plantation is one of several commercial poplar plantations on former agricultural land owned by a forestry company Hällefors Tierps Skogar AB.

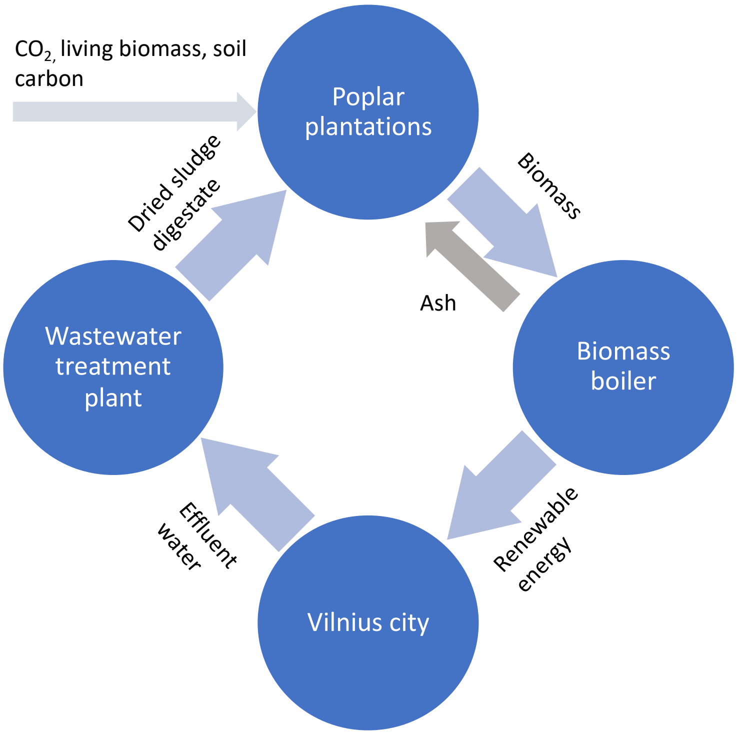



*Figure 1. The closed-loop circular economy model of nutrient-rich waste recycling tested in Vilnius, Lithuania, developed within the 'NutriBiomass4LIFE' project.*

# 2. Materials and methods

## 2.1 Site description

The poplar plantation is located in the coniferous-dominated landscape outside Hillebola, central Sweden (blocks 1 and 2 - 60.351975 N, 17.690794 E; blocks 3 and 4 - 60.349752 N, 17.667424 E). The area of set-aside arable land, approximately 25-30 hectares, was planted in 2016 with *Populus trichocarpa* clones adapted to northern European climate by breeding (Adler *et al*., 2023; Adler *et al*., 2021; Apuli *et al.*, 2021; Karacic *et al*., 2021; Richards *et al*., 2020; Ronnberg-Wastljung *et al*., 2022; Vico *et al*., 2021). The parcel with blocks 1 and 2 was previously grown with food and fodder crops, while blocks 3 and 4 were established on grassland (Figure 2).
Block 1 was established on a slope with a slight inclination, while all other blocks were situated at lower elevations in the terrain. In the past, both fields were ditched along the lowest isohypses to enhance 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 the light-textured soil in blocks 3 and 4 (Tables 1 and 2).

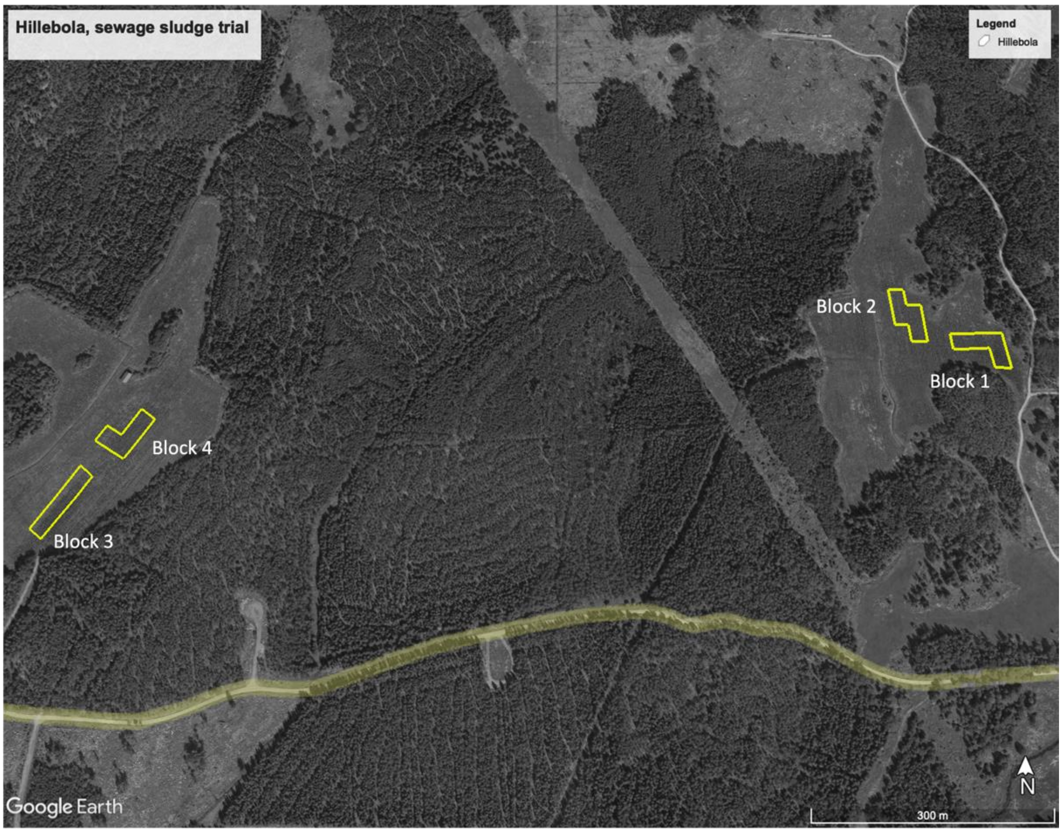



*Figure 2. The four blocks of the Hillebola trial are placed on two nearby fields. The soil characteristics and previous land use of these two fields were different.*

Four weeks prior to plantation, the fields were treated by the herbicide Roundup. The plantation was established by planting bare-root plants (rooted cuttings) of above-mentioned provenance hybrids of *Populus trichocarpa* bred at the Swedish University of Agricultural Sciences. Establishment was successful, and early growth was satisfactory despite a lack of weed management. At the end of the third growing season and before our experiment started, the average tree diameter at breast height (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. In the random treatment application, initial planting densities varied among treatments, ranging from the lowest average density in control plots (1,381 trees $ha^{-1}$) to the highest in NPK plots (1,520 trees $ha^{-1}$).. We accounted 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 15 × 15 = 225 $m^2$ in the center of the larger plots. The spacing of a plot was estimated within the net plot. Four treatments were applied: i) mineral NPK fertilizer + soil cultivation between poplar rows, ii) dried pelletized sludge + soil cultivation, iii) no fertilization + soil cultivation only, and iv) control i.e., no fertilizer or soil cultivation. The row spacing was too narrow to enable entering the plantation with commercial granular spreaders. Instead, the pelletized sludge was distributed between poplar rows by a sand spreader attached to a small tractor. A small shallow plough was used for the cultivation treatment and to mix the mineral fertilizer or pelletized sludge into the soil (Figure 5). Other implements, such as a rotary cultivator, could not fit between the tree rows. The mineral NPK fertilizer was spread manually.

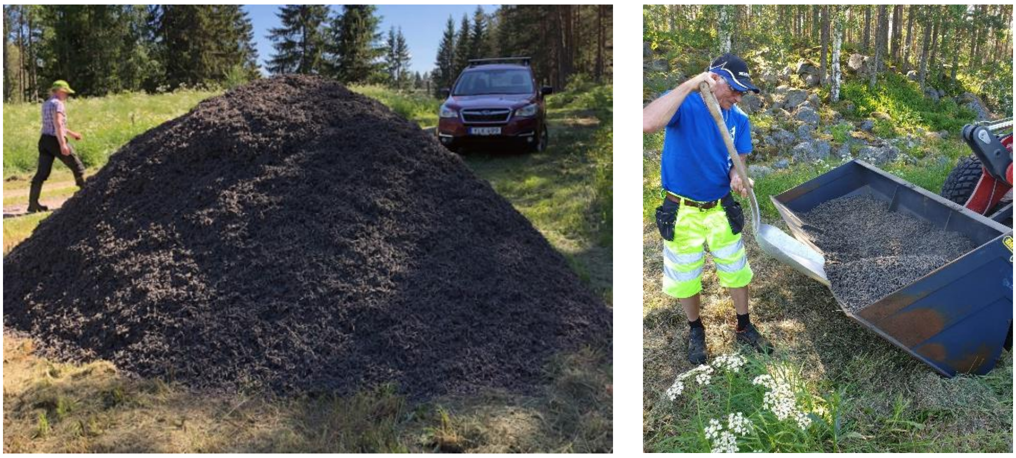
*Figure 3. A view over the location of block 1 in May 2019, one month before the treatment application.*

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

*Figure 5. On the left: treatments were applied at the beginning of June 2019 using a small tractor that could fit between the densely planted poplar rows in Hillebola. On the right: a shallow plough 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 con-tained 90% of the dry matter and was not REVAQ certified (Figure 6, Table 3).



*Figures 6. Dried pelletized sludge was delivered in the beginning of June 2019 from Moravatten AB (on the left). The sludge was spread in the experimental plots on the same day (on the right).*

*Table 1. 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 2. Soil heavy metal content for the two fields in Hillebola before the treatment with pelletized 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 |

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 1994:2). 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 4). After spreading, the sludge was worked into the soil.

*Table 3. Extract from the analysis of pelletized sludge from Moravatten AB used for fertilization in the Hillebola trial. The limiting values for heavy metals in the 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 4. The amount of applied sludge was based on the limiting amounts of added P and heavy metals.*

| Sludge chemical elements | Calculated dosage of dried pelletized 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 harvested poplar trees was used to construct the growth model and estimate the leaf area of harvested trees. The treatment effects were assessed using the plot basal area (BA) as 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 quadrats per block and treatment, 64 quadrats in total, were laid systematically to obtain a representative sample of the ground vegetation cover. The size of the quadrats was $0.5 \times 0.5 = 0.25\ m^2$. Three out of four quadrats were positioned between poplar rows to cover the vegetation occurrence of the cultivated area within the plots. The same positioning pattern, three between and 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 biomass of ground vegetation within the $0.25\ m^2$ sample quadrats was cut, dried to a constant weight at 95°C, and weighed. The biomass from the sample quadrats was then upscaled to an area unit of one hectare (Figure 7).

*Figure 7. The sampling procedure for ground vegetation in the poplar plantation in Hillebola was conducted at the beginning of September 2019. The herbaceous vegetation occurred mostly on cultivated soil between the poplar rows (on the right), had less biomass compared to control plots (on the left), 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 systematically collected, with one leaf per tree taken at a two-meter height from 2/3 of the branch length, oriented towards the east—*i.e.*, facing the area between rows aligned in a south-north direction.

### 2.4.4 Damage

The poplar plantation in Hillebola was not fenced, and some moose 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 was observed throughout the location, with particularly severe damage in fertilized plots. The consequence of ring-barking on trees led to their death in 2021 and 2022, which, in turn, hindered the follow-up estimates of the growth performance of poplar trees.

## 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 net 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. Basal area (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 (Tables 5 and 6, Figure 8). The BAI was significantly higher in NPK and sludge treatments compared to the control, but not in the cultivation treatment without fertilizer application (Table 6). The positive effect of NPK treatment was expected due to a high dosage of mineral nitrogen per hectare (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 3). Both NPK and sludge treatments showed a higher BAI compared to cultivated, non-fertilized plots, even though the significance of these differences could not be statistically confirmed within the actual trial design.

*Table 5. The ANCOVA table for the analysis of logarithm-transformed basal area increment (lnBAI) as dependent on block and treatment. The initial basal area of trees (lnBA18) before the experiment was started, in May 2019, was introduced as covariance to compensate for the effect of tree size (initial DBH) on growth two growing seasons later.*

| Cases | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Block | 0.278 | 3 | 0.093 | 5.452 | 0.025 |
| Treatment | 0.513 | 3 | 0.171 | 10.059 | 0.004 |
| BA18ha ($m^2$) | 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 retained 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 Driessche *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.

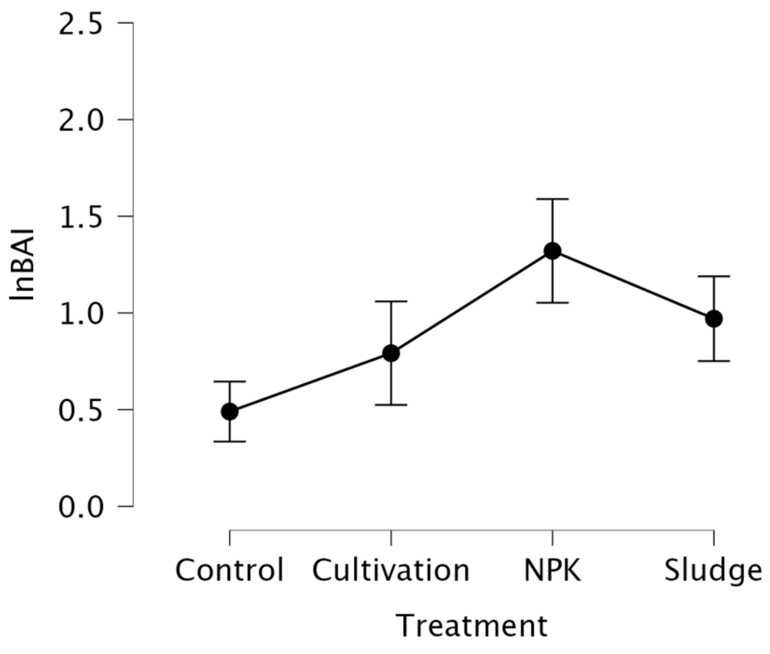



*Figure 8. The effects of fertilization and cultivation treatments on the basal area increment (BAI) two growing seasons after the application of following treatments: Control (no soil cultivation, no fertilization), Cultivation (soil cultivation only), NPK (fertilization with mineral fertilizer + soil cultivation), Sludge (fertilization withdried pelletized sludge + soil cultivation).*

*Table 6. 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 (Figure 9). As poplar trees are very efficient in recycling nitrogen within the system, it can be expected that these increased N levels will contribute to permanently increased yields. The levels of leaf-N in control and soil 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 (Figure 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 vegetation in 2023, which is three years after the initial sampling (Figure 11). This is in contrast to the state in autumn 2019, when the aboveground ground vegetation weighed 4.1 tons $ha^{-1}$ as indicated in Figure 10).

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.

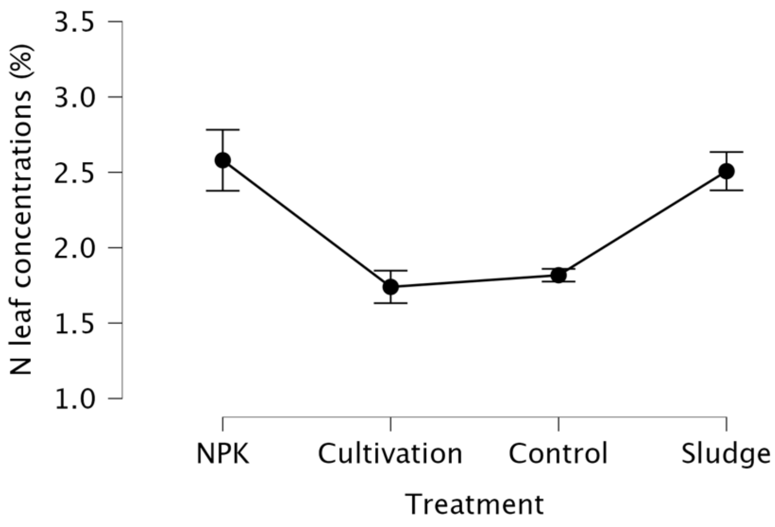



*Figure 9. The concentration of nitrogen (%) in leaves of trees grown in Hillebola at the end of the first growing season after applying treatments: NPK (fertilization with mineral fertilizer + soil cultivation), Cultivation (soil cultivation only), Control (no soil cultivation, no fertilization), Sludge (fertilization with dried pelletized sludge + soil cultivation).*

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 (Figure 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.

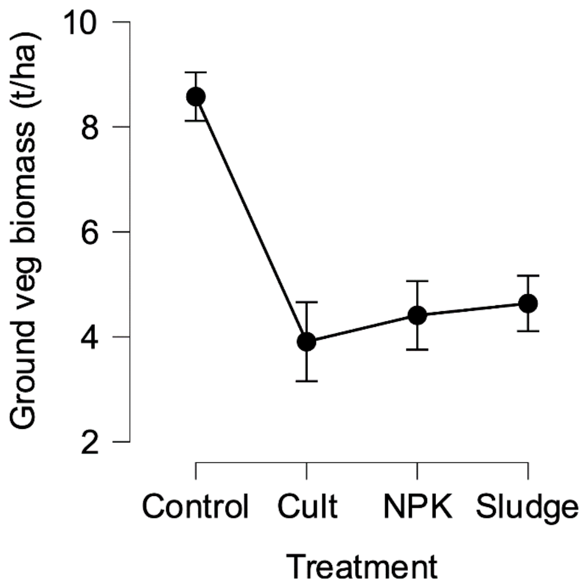



*Figure 10. The ground vegetation biomass (tons $ha^{-1}$) in September 2019 in the following treatments: Control (no soil cultivation, no fertilization), Cult (soil cultivation only), NPK (fertilization with mineral fertilizer + soil cultivation), Sludge (fertilization withdried pelletized sludge + soil cultivation).*

*Figure 11. Four years after the sampling of ground vegetation in the NPK treatment in block one, during the summer of 2023, the ground vegetation cover had disappeared due to canopy closure. Canopy closure had already eliminated the ground vegetation layer in 2022. As the canopy closes, additional nutrients become available to the poplars through the mineralization of nutrients bound in the ground vegetation.*

# 4. Conclusions and Practical Recommendations

Despite its limited scope, the Hillebola trial demonstrated the potentially positive effects of fertilization 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. A substantial amount of ground vegetation cover in the young poplar plantations, contributed to the soil carbon pool. Additionally, a portion of the nutrients applied with sludge is captured by the ground vegetation. The nutrients released through the subsequent mineralization of this biomass pool will likely serve as an additional nutrient source for a closing canopy in young poplar stands.
3. The efficient sludge spreading in poplar plantations requires spacings with at least 3.3 m between the rows.

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