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Effect of Wood Ash, Lime, and Biochar on the Establishment and Early Growth of Poplars on Acidic Soil Conditions

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Abstract

Poplars are traditionally cultivated on arable land, but other land types, such as forested land and forested arable land, may also provide significant opportunities for poplar plantations without competing with food production. However, these sites often have suboptimal soil pH levels that hinder optimal poplar growth, highlighting the need for improved establishment methods to enhance both survival and growth. This study investigates the establishment and growth of poplars (*Populus trichocarpa* and their hybrids) at forest land and forested arable land after application of wood ash, lime, and biochar using three different application methods: (i) amendment spread on the soil (Surface), (ii) amendment mixed with the soil (Mixed), (iii) amendment placed on the planting spot (Spot). Our findings revealed that wood ash and lime application almost double growth compared to untreated plants, 3 years after planting, and that growth increased equally independently whether wood ash or lime was mixed with the soil or applied on the soil surface while Spot application method resulted in overall lower growth than the Mix and Surface method. In contrast, biochar application had a lower effect on tree growth compared to wood ash and lime. This study highlights the potential of using wood ash to improve poplar growth on sites with low soil pH and that application methods can be adapted for different site conditions, thereby supporting the early establishment of these fast-growing plantations in sites with suboptimal soil conditions.

Keywords *Populus* · *P. trichocarpa* · Poplar plantation · Forest land · Forest arable land · Soil amendment

Highlights

- Wood ash and lime application enhanced poplar growth in both forest and forested arable land.
- Wood ash enhanced growth in a wider soil pH range compared to lime.
- Biochar application had limited impact on early poplar growth.
- Application methods Mixed or Surface resulted in similar growth increment.
- Wood ash application on forested arable land shows potential for enhancing the establishment of poplar plantations in Sweden.

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Introduction

Transitioning to fossil-free and zero-carbon energy systems is essential for meeting climate goals and reducing CO_2 emissions. The European Commission has recommended afforestation of former agricultural lands as a sustainable land management practice to simultaneously contribute to CO_2 mitigation, biodiversity enhancement, and an increased supply of woody biomass [1]. This growing demand for bio-based resources is driven by the expanding production of existing products and the development of new bio-based materials, putting pressure on current biomass supplies which may fall short of future needs. One effective strategy to bridge this gap is to maximize biomass yield per unit area by planting fast-growing, early-successional tree species, such as *Populus*, combined with effective management practices over large areas.

In Sweden, approximately 500,000 hectares of arable land, 2.5 million hectares of forest land, and an additional 1.2 million hectares of arable land (forested arable land) that has transitioned to forested land over the past 70 years could be available for establishing *Populus* plantations [2, 3]. Forested arable land, while maintaining characteristics of high soil fertility and water-holding capacity both important for fast-growing broadleaf species, has often undergone soil acidification, especially following one 70–80 years long rotation with Norway spruce (*Picea abies* Karst) [4, 5]. Given the potential production of *Populus* plantations at these sites that can reach 6 Mg ha^{-1} $year^{-1}$, there is a significant incentive to investigate treatments that could enable poplar growth on sites with sub-optimal soil pH, especially considering that the usage of a fraction (25%) of these areas could supply up to 10 TWh of biomass annually without competing with food or feed production [2]. Furthermore, the increasing frequency of insect pests and storms over the past two decades has compelled foresters to consider alternatives to spruce at forest land and forested arable land.

Poplars (*Populus trichocarpa* Torr. & A.Gray ex Hook., *Populus maximowiczii* A.Henry and their hybrids) are known to be nutrient and water demanding and require a soil pH > 5 for optimal growth; below this, growth reductions are common due to nutrient limitations and increased susceptibility to aluminum (Al) toxicity [6–9]. Low soil pH can impair plant development in several ways, including increased mortality from high proton (H^{+}) levels, inhibited water uptake, and deficiencies in essential nutrients such as phosphorus (P) and calcium (Ca), as well as toxicities from increased availability of metal ions such as aluminum (Al), manganese (Mn), and magnesium (Mg) [10–14]. Specifically, soluble Al^{3+} ions are one of the main chemical constraints on plant growth in acidic soils by inhibiting root elongation [15, 16], altering ion fluxes, disrupting membrane channels, and interfering with nutrient uptake [17–21]. For poplars, Al^{3+} sensitivity has been suggested to be one of the factors limiting poplar establishment and growth in acidic conditions [9, 22, 23].

Application of lime or wood ash can increase soil pH [24–27]. Some studies show positive growth effects after liming [28–30] while other studies report neutral growth effects [22, 31, 32] and even negative effects [22, 24, 33]. Similarly, wood ash's effect on growth is variable, with studies reporting increased growth [34–40] but others reporting neutral or negative effects [26, 31, 41–43]. Besides increasing soil pH, liming and wood ash application can result in an addition of macro- and micronutrients. Liming primarily adds calcium (Ca) and magnesium (Mg) while wood ash supplies additional phosphorus (P) and potassium (K) [44]. Application of biochar can also affect plant growth by improving soil moisture retention, increasing nutrient availability, and reducing soil toxicity by adsorbing toxic ions like Al^{3+} [45–47] but similar to lime and wood ash, growth effects are variable with studies reporting positive [46, 48], neutral [49, 50], or negative effect [51]. As poplars rely on fast growth to establish, early access to soil water and nutrients is critical for newly planted seedlings [52, 53], with studies showing that root systems can extend over a meter during the first year [54]. As such, soil amendments aimed at improving soil proprieties must have a rapid effect to support the establishment and early growth phases for poplar seedlings. However, the amendment effect on plant growth is complex and varies based on factors such as soil proprieties, amendment composition, and application method, thus resulting in variable growth effects.

Despite studies on individual methods [23, 28, 30], limited research has directly compared different application methods to assess their impact on poplar growth in acidic soils on forest land and forested arable land. To address this knowledge gap, we conducted an experiment on forest land and forested arable land. The objectives of this study were to (1) evaluate the early growth response of *P. trichocarpa* and its hybrids to soil treatments with wood ash, lime, and biochar in forest and forested arable land and (2) examine the influence of different application methods of these amendments on the early growth and establishment of poplars, ultimately supporting high productivity and biomass supply on land unsuitable for food production.

Materials and Methods

Site Description and Climate Conditions

The experimental sites are located in southern Sweden (Fig. 1) and were established between 2019 and 2020. The experiment was placed at two site types: (i) forest land sites (For) with a continuation of forest coverage for more than 100 years and (ii) forested arable land sites (ArFor), i.e., former agricultural land planted with one rotation of Norway spruce that was grown for 40 to 70 years (Fig. 1). Prior to the experiment establishment, a homogeneous newly clear-felled area was selected at each site to undergo planting of the experiment. Temperature and precipitation were recorded at a local weather station within 10 km of the sites Table 1.

Plant Material

Plants were produced by first collecting dormant cuttings in February. These were thereafter stored at 4 °C until planting. In spring, i.e., April, cuttings were planted in containers 250 ml containing plant nursery soil mixture consisting of 83% peat, 5% clay, 7% gravel, 7% hydrograins, and N-P-K 11–5–8 plus micronutrients with a pH of 5.5–6.5 and grown to approximately a height of 40 cm and diameter of about 5 mm under field conditions. The plants were stored at + 2 °C during the following winter before planting in spring 2020. At the time of the planting, the poplar seedlings were 1 year old.

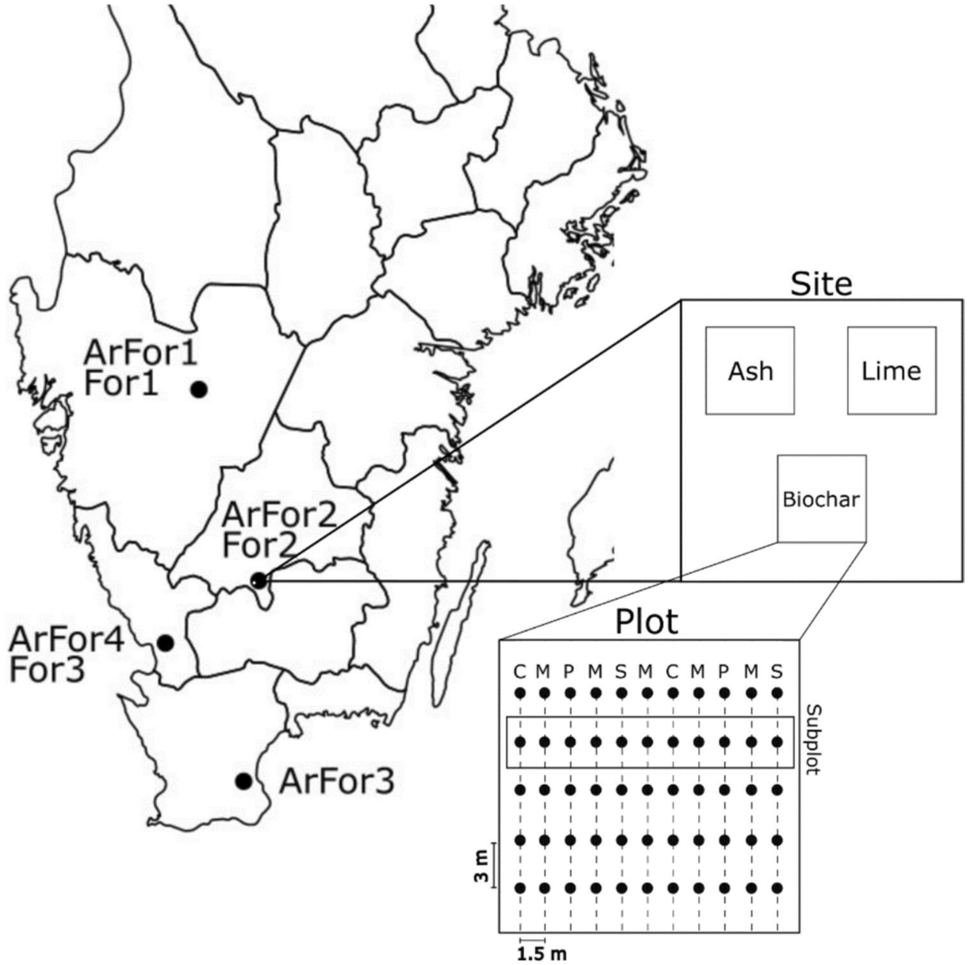

Fig. 1 Map of southern Sweden marked with the experimental sites and the experimental design used at all sites. Sites are marked as forested arable land (ArFor, i.e., former agricultural land planted with one rotation of Norway spruce that was grown from 40 to 70 years sites) and forest sites (For, i.e., used as forest land for more than 100 years). Note that ArFor1-For1, ArFor2-For2, and ArFor4-For3 are located less than 1 km from each other; thus, only one point represents two sites. Each site is divided in three plots (ash, lime, and biochar). Application methods are shown as mixed (M), surface (S), spot (P) and untreated, i.e., control (C) columns. Each planting position is shown with a filled circle. The spacing between the tree rows was 3 m while between plants was 1.5 m; the plot size was in total 18 × 18 m

Table 1 Description of experimental sites and their climatic conditions

Site	Latitude °N	Longitude °E	Precip, mm/year	Mean temp, °C	Site index
For1	58°27′12.8″N	13°38′41.8″E	740	7	G32
For2	57°00′38.4″N	14°22′16.7″E	780	6	T28
For3	56°42′03.6″N	13°05′21.7″E	920	5	G32
ArFor1	58°27′56.9″N	13°34′09.8″E	740	8	G32
ArFor2	57°02′07.5″N	14°20′10.7″E	780	6	G32
ArFor3	55°41′28.3″N	14°05′42.0″E	660	8	G36
ArFor4	56°39′45.6″N	13°03′57.0″E	920	5	G34

Site index (SI) corresponds to the dominant height of Norway spruce (G) or Scots Pine (*Pinus sylvestris* L.) (T) at an age of 100 years. Mean temperature is the yearly average temperature in °C since 2005. Precipitation represents the average yearly precipitation (mm) since 2005

At all sites, mechanical soil preparation in rows was performed using an excavator. The planted clones at site For1, For3, ArFor1, ArFor3, and ArFor4 were clone Androscoggin (*P. maximowiczii* × *P. trichocarpa*), clone Rochester (*P. trichocarpa* × *P. nigra*), clone 14 (*P. trichocarpa*), and OP42 (*P. maximowiczii* × *P. trichocarpa*), and at site For2 and ArFor2, SnowTiger® SLU clones "23.4," "26.1," "44.7," and "722.16" (all provenance hybrids within *P. trichocarpa*; [55]) were planted. In this study, the different *Populus* species and hybrids are referred to as poplar.

Experimental Design

At each site, plants were planted in plots treated with either ash (3 Mg ha^{-1}), lime (3 Mg ha^{-1}), or biochar (20 Mg ha^{-1}), as well as in untreated control plots. Within each plot, five subplots were designed, each containing three application methods:

(i) Mixing method (Mixed): where the amendment was mixed with the soil in a 1 × 1 m^2 to a depth of about 30 cm
(ii) Surface method (Surface): where the amendment was evenly applied to the soil surface 1 × 1 m

(iii) Planting spot method (Spot): where the amendment was applied in a 0.3-m diameter cylinder hole
(iv) Untreated (Control): no amendment was applied

The spacing between plants in each subplot was 1.5 × 3 m and all subplots were randomly distributed within the plots (Fig. 1). The experiment was fenced to prevent browsing damage and manually planted using a shovel. Within each treatment plot (wood ash, lime and biochar), 25 plants were treated using the Mix method, while 10 plants were treated with Surface and Spot methods, and 10 plants were designated as untreated Control.

At sites For1, For3, ArFor1, ArFor3, and ArFor4, the Mix-treated plots were planted with the clones (number of transplants under brackets): "OP42" (7), clone "Androscoggin" (6), clone "Rochester" (6), and clone "14" (6). For the Surface, Spot, and Control treatments, the planting configuration included clone "OP42" (3), clone "Androscoggin" (3), clone "Rochester" (2), and clone "14" (2). At sites For2 and ArFor2, the Mix-treated plots included clone "722.16" (7), clone "26.1" (6), clone "44.7" (6), and clone "23.4" (6). Similarly, for the Surface, Spot, and Control treatments, the planting scheme consisted of clone "722.16" (3), clone "26.1" (3), clone "44.7" (2), and clone "23.4" (2). More information about the clones deployed in the study can be found in supplement S3.

Lime, Wood Ash, and Biochar

The pulverized calcitic lime used was Ingaberga 0–0.02 mm, Nordkalk AB, Hässleholm Sweden, produced by grinding limestone to a particle size of 0–0.02 mm.

Biochar was produced by pyrolysis (750 °C) of barley and wheat seed residue pellets 4 × 20 mm in a Pyreg® pyrolysis unit. Wood ash was produced by combustion of forest residues, branches, and tops of *Pinus sylvestris* L. and *Picea abies* Karst in a commercial biomass boiler. The type of wood ash used in this study was 95% bottom and 5% fly ash. Samples of wood ash were analyzed at ALS Scandinavia AB, Luleå, Sweden, using analysis of metals in solid matrices with ICP-SFMS according to SS-EN ISO 17294–2:2023 and US EPA Method 200.8:1994 after digestion of samples according to S-PS49-FU. The chemical characteristics of the biochar used were analyzed by determination of selected elements by inductively coupled plasma optical emission spectrometry in accordance with DIN EN ISO 11885 (E22): 2009–09 and DIN 51732:2014–07. Analysis results of the wood ash, lime, and biochar are shown in Table 2.

Table 2 Elemental analysis of wood ash, lime, and biochar used in this study

Element/compound	Lime	Wood ash	Biochar
Bulk density (kg/m^3)	881	412	291
P (%)	0	3.6	16.5
Ca (%)	50.1	34.1	12.8
Mg (%)	0.5	8.6	6.9
Na (%)	0	0.5	0.8
K (%)	0	10.4	26.4
Zn (mg/kg)	0	1950	144
Fe (%)	0	1.4	0.9
Mn (%)	0	4.0	0.02
Si (%)	0	8.3	30.4
Cd (mg/kg)	0	22.2	< 0.02
Pb (mg/kg)	0	23.1	< 2
Cr (mg/kg)	0	542	5.0
Ni (mg/kg)	0	58.2	4.0
C (%)	0	48.2	78.3
N (%)	0	0.3	2.9
C/N	0	160.7	27.0
pH	12.3	12.1	10.1

% is shown as percentage of dry weight (DW)

Measurements and Soil Analyses

Survival, stem height, and root collar diameter (10 cm above the soil surface) were recorded at planting and after first, second, and third years of growth. To determine the effect on soil chemistry, 12 soil samples in untreated, ash, lime, and biochar (Mixed method) plots were sampled at a depth of 30 cm and pooled to generate one sample for each site. The samples were collected 3 years after application. Soil samples were analyzed at Eurofins Agro Testing Sweden AB in Kristianstad, Sweden, using ammonium lactate/acetic acid solution (the AL-Method) in accordance with the method SS 028310:1995–12 and by inductively coupled plasma optical emission spectrometry in accordance with the method ISO 11885:2009–09. The results are presented in Table 3.

Statistical Analysis

All data analyses were implemented in R version 4.4.1 [56]. To test the effect of soil amendments and their application method on tree growth (i.e., tree height and root collar diameter), we used linear mixed-effects models implemented in the "lme4" package [57]. Survival as a Boolean variable was tested using generalized linear mixed models implemented in the "glmmTMB" package [58]. The response variables tested were tree height, root collar diameter, and survival. Site type (For and ArFor), amendment (wood ash, lime, and biochar), application method (Mixed, Surface, Spot, and Untreated), and their interactions were set as fixed effects while site was treated as a random effect. To evaluate statistical differences among treatments, Tukey's HSD post hoc test, implemented in the "emmeans" R package [59] was used. A $p \leq 0.05$ was used as

Table 3 Analysis of the soil properties and elements content. Mean values across sites for soil chemistry parameters (pH, N, P, K, Ca, Mg, Mn, Cu, Fe, Zn, CEC, and BS) before and after treatments (biochar, lime, and ash) at forested arable land (ArFor) and forest land (For)

	Treatment	pH	N (mg/kg)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Zn (mg/kg)	CEC (meq/100 g)	BS (%)
ArFor	Untreated	4.9	19.9	1.7	1.8	16.8	1.2	9.3	0.2	213	2.4	13.7	5.1
	Biochar	5.5	3.8	3.3	7.7	37.4	4.3	21.8	0.6	260	2.9	15.1	14.8
	Lime	6.0	5.8	3.4	3.7	113	5.5	6.8	0.4	227	1.0	15.4	32.0
	Ash	5.8	2.5	4.8	6.7	76.9	8.3	55.5	0.7	234	4.8	15.3	29.8
For	Untreated	4.6	13.4	1.7	1.4	7.8	0.7	5.9	0.2	447	0.4	10.3	2.8
	Biochar	5.1	3.2	3.0	4.9	10.5	3.0	7.2	0.6	440	1.5	16.2	6.3
	Lime	5.0	5.0	2.9	3.7	19.5	4.0	8.8	0.5	550	1.9	16.5	9.2
	Ash	5.4	2.6	2.9	5.6	32.2	6.7	43.3	0.7	490	2.2	15.2	19.0

Untreated values represent soil chemistry in untreated plots, while biochar, lime, and ash values reflect post-treatment effects with the corresponding amendment. Parameters include pH, total nitrogen (N, mg/kg), phosphorus (P, mg/kg), potassium (K, mg/kg), calcium (Ca, mg/kg), magnesium (Mg, mg/kg), manganese (Mn, mg/kg), copper (Cu, mg/kg), iron (Fe, mg/kg), zinc (Zn, mg/kg), cation exchange capacity (CEC, meq/100 g), and base saturation (BS, %). Values for P, K, Ca, Mg, Mn, Cu, Fe, and Zn represent the plant available concentration

the cutoff for statistical significance. Residuals showed normal distributions with no high-leverage outliers using "DHARMa" package [60].

To analyze the effect of wood ash, lime, and biochar on tree height after three growing seasons in Mixed application method in relation to soil characteristics (pH, N, P, K, Al, Ca, and Mg), linear regression was used.

Results

Plant Survival

Three years after planting, plant survival was affected by wood ash, lime, or biochar and their application method (Table 4). On forest land (For), survival of plants treated with wood ash, lime, or biochar was found to be higher compared to untreated plants, varying between 68 and 97% depending on the application method. On forested arable land (ArFor), lime-treated plants displayed higher survival rates among all application methods compared to untreated plants while only wood ash and biochar with Mixed method resulted in increased plant survival compared to untreated plants. There were though no differences found for survival when wood ash and biochar were applied with Surface method (Table 4). These differences were not observed in the first 2 years after planting (Table 4).

Lime and Wood Ash Increased Tree Growth at Forest and Forested Arable Land

Across application methods, wood ash and lime increased tree growth at For and ArFor (Table 5). At For, tree heights on the ash-treated soil were 206%, 238%, and 227% of the heights of the untreated trees in the first, second, and third year after planting, respectively. At ArFor, the corresponding heights were 123%, 140%, and 148% of the untreated trees in years 1, 2, and 3, respectively.

Similar to tree heights, root collar diameters on ash-treated soil were 228%, 243%, and 267% of the diameters of the untreated trees after the first, second, and third year, respectively. At ArFor, the corresponding diameters in the first, second, and third year after planting were 131%, 148%, and 162%, respectively. There were differences between the treatments with wood ash being the most effective and biochar the least effective in increasing tree growth (i.e., height and diameters) the third year after planting at both For and ArFor (Table 5).

Mixing Wood Ash or Lime with the Soil or Applying the Amendment on the Soil Surface Increased Growth of Poplars Similarly

At the ArFor sites, ash-treated plants with the Mixed method resulted in plants reaching a mean height of

Table 4 Plant survival rates (%) in forest land (For) and forested arable land (ArFor) after application of wood ash, lime, or biochar using the application methods Mixed, Surface, and Spot

	Treatment	Method	Year one		SE		Year two		SE		Year three		SE	
For	Ash	Untreated	90.7	±	4.4	a	83.6	±	5.5	a	62.2	±	7.5	a
		Mixed	97.6	±	1.8	a	97.4	±	1.9	a	95.0	±	3.8	b
		Surface	100.0	±	0.0	a	96.0	±	3.3	a	96.9	±	7.6	b
		Spot	87.5	±	6.7	a	90.2	±	5.7	a	90.6	±	8.0	b
	Lime	Untreated	83.9	±	6.0	a	70.3	±	7.3	a	30.7	±	7.8	a
		Mixed	94.9	±	2.8	a	88.2	±	4.3	a	86.4	±	4.8	b
		Surface	96.7	±	3.2	a	96.8	±	3.3	a	87.7	±	6.4	b
		Spot	96.7	±	3.2	a	96.8	±	3.3	a	90.8	±	5.5	b
	Biochar	Untreated	88.8	±	4.9	a	83.6	±	5.5	a	31.0	±	7.8	a
		Mixed	87.2	±	4.9	a	85.6	±	4.8	a	68.7	±	7.4	b
		Surface	80.6	±	8.4	a	83.6	±	7.3	a	77.5	±	8.7	b
		Spot	93.7	±	4.7	a	90.2	±	5.7	a	80.8	±	8.0	b
ArFor	Ash	Untreated	90.3	±	3.9	a	74.8	±	6.0	a	56.5	±	7.5	a
		Mixed	93.6	±	2.7	a	89.2	±	3.4	b	87.3	±	3.8	b
		Surface	89.7	±	4.7	a	81.8	±	6.0	ab	71.8	±	7.6	ab
		Spot	91.3	±	4.2	a	72.0	±	7.4	a	67.8	±	8.0	a
	Lime	Untreated	89.6	±	4.1	a	80.8	±	5.2	a	61.5	±	7.3	a
		Mixed	97.6	±	1.5	a	90.7	±	3.1	a	84.1	±	5.7	b
		Surface	94.9	±	3.1	a	94.6	±	3.2	a	86.6	±	4.0	b
		Spot	89.7	±	4.8	a	87.3	±	5.0	a	94.1	±	3.5	b
	Biochar	Untreated	94.3	±	2.8	a	80.6	±	5.2	a	64.1	±	7.1	a
		Mixed	96.1	±	2.0	a	88.0	±	3.6	a	82.9	±	4.6	b
		Surface	96.7	±	2.5	a	90.8	±	4.2	a	79.5	±	6.7	ab
		Spot	98.4	±	1.7	a	96.4	±	2.6	a	85.7	±	5.6	ab

Data shown represent survival rates in % across experimental sites. Letters represent statistical differences ($p \leq 0.05$) between application methods within the same type of amendment and site type

225 cm, followed by Surface (200 cm), Spot (160 cm), and untreated plants (140 cm) (Fig. 2A) with no differences between Mixed and Surface application methods (Fig. 2A). This was also found for diameter growth at For and ArFor sites, with the Surface method resulting in similar diameters as Mixed (Fig. 3A and D). At the For sites, ash application resulted in similar height growth increment between Mixed and Surface application methods with plants reaching mean heights of 200 cm and 180 cm, respectively (Fig. 2D).

For lime-treated plants, the effect of different application methods followed a similar pattern, with Mixed method reaching an average height of 170 cm followed by Surface (165 cm), Spot (160 cm), and untreated (130 cm) (Fig. 2B) with no significant differences between Mixed and Surface (Fig. 2B). At For sites, application of lime resulted in no differences between the application methods, all reaching a height of 145–148 cm (Fig. 2E) but compared to untreated plants, height growth was increased (Fig. 2E). Diameter growth with Mixed and Surface resulted in similar increments (Fig. 3B and E).

In conclusion, amendments using Mixed and Surface application methods were similarly effective in increasing tree growth at For and ArFor.

At ArFor sites, all application methods with biochar did not alter height and diameter (Figs. 2C and 3C). In For sites, untreated plants reached a mean height of 65 cm and 6 mm diameters while treated plants had heights of roughly 95 cm to 100 cm and 11 mm to 15 mm in diameter. However, no significant differences ($p > 0.05$) were detected (Figs. 2F and 3F) for all the application methods.

Impact of Treatment on Plant Height at Different Soil Characteristics Levels

The ash-treated plants consistently outperformed the untreated plants across all pH, aluminum (Al), and potassium (K) levels, achieving heights exceeding 200 cm, whereas the untreated plants only reached 100–110 cm (Fig. 4A, J, and M). Phosphorus (P) content in the soil had a stronger positive impact on untreated plants ($R = 0.41$, $p = 0.004$) than on treated plants ($R = 0.18$, $p = 0.023$),

Table 5 Plant height (cm) and root collar diameter (mm) after the application of wood ash, lime, and biochar in forest land (For) and forested arable land (ArFor)

		Year one								Year two			
	Treatment	Height		SE		Diam		SE		Height		SE	
For	Untreated	35.8	±	7.0	a	2.8	±	0.3	a	56.6	±	5.2	a
	Biochar	40.9	±	6.8	a	3.7	±	0.4	b	73.1	±	4.6	b
	Lime	53.8	±	6.8	b	4.5	±	0.5	c	94.6	±	4.6	c
	Ash	73.9	±	6.8	c	6.4	±	0.7	d	134.5	±	4.5	d
ArFor	Untreated	61.6	±	6.1	a	4.9	±	0.5	a	99.2	±	4.8	a
	Biochar	67.2	±	5.9	a	5.7	±	0.5	b	112.2	±	4.0	ab
	Lime	69.1	±	5.9	ab	5.7	±	0.5	b	113.8	±	4.0	b
	Ash	75.7	±	5.9	b	6.4	±	0.6	c	139.2	±	4.1	c
		Year two				Year three							
	Treatment	Diam		SE		Height		SE		Diam		SE	
For	Untreated	6.0	±	0.5	a	85.8	±	11.5	a	8.1	±	0.7	a
	Biochar	8.3	±	0.6	b	105.2	±	9.8	b	11.1	±	0.8	b
	Lime	10.3	±	0.7	c	140.8	±	9.5	c	14.8	±	1.1	c
	Ash	14.6	±	1.0	d	194.5	±	9.3	a	21.6	±	1.6	d
ArFo	Untreated	8.6	±	0.6	a	145.8	±	9.5	a	12.1	±	0.9	a
	Biochar	10.2	±	0.6	ab	173.4	±	8.4	b	15.3	±	1.0	b
	Lime	9.9	±	0.6	b	181.3	±	8.2	b	15.5	±	1.0	b
	Ash	12.7	±	0.8	c	215.9	±	8.2	c	19.6	±	1.3	c

Data shown represent mean height and diameter of trees in each of the three years after planting. Letters represent statistical differences ($p \leq 0.05$) between treatments within the same site type

with ash-treated plants reaching 200 cm height at low P concentrations while untreated plants reached 100 cm at the same P level (Fig. 4G). Additionally, ash-treated plants performed better at low calcium (Ca) and magnesium (Mg) levels but similarly to untreated at higher concentrations (Fig. 4P and S).

Lime application was most effective under low pH and phosphorus (P) concentrations, with treated plants reaching 160 cm compared to 90 cm for untreated plants (Fig. 4B and H). However, at higher pH and P levels, both lime-treated and untreated plants showed similar heights (Fig. 4B and H). Potassium (K) had a similar impact on both lime-treated and untreated plants ($R = 0.35$, $p < 0.001$ and $R = 0.28$, $p = 0.092$, respectively), but treated plants consistently grew taller across all K levels (Fig. 4K). Aluminum (Al) negatively affected treated plants ($R = -0.21$, $p = 0.012$), resulting in 180 cm heights at lower Al levels and 140 cm at higher levels, similar to untreated plants (Fig. 4N). Lime-treated plants performed better under low calcium (Ca) and magnesium (Mg) levels but similarly to untreated plants at higher levels (Fig. 4Q and T). Nitrogen (N) positively influenced growth in both lime-treated and untreated plants ($R = 0.32$, $p < 0.001$ and $R = 0.39$, $p = 0.018$, respectively) (Fig. 4E).

In contrast to wood ash and lime, biochar application did not influence growth performance of poplars for any soil parameters analyzed (Fig. 4C, F, I, L, O, R, and U).

Discussion

Poplar plantations have traditionally been established on arable or agricultural land [61]. However, forested and forested arable lands present a significant, largely untapped potential for poplar cultivation, with several million hectares available in Sweden [2, 3]. Despite this, these areas have not been planted as they often have acidic soil conditions that can negatively impact poplar growth [5, 28, 62]. Our findings reveal that soil amendments such as wood ash and lime—and to a lesser extent, biochar—effectively enhance growth on both forest and forested arable sites (Table 5, Figs. 2 and 3), where soils tend to be acidic (Table 3).

These results are consistent with previous research showing growth benefits from wood ash, lime, and biochar treatments on tree species, including poplars, in acidic conditions [28, 30, 34, 63–66]. Specifically, wood ash and lime application almost doubled the growth of poplars compared to untreated, suggesting that when soil

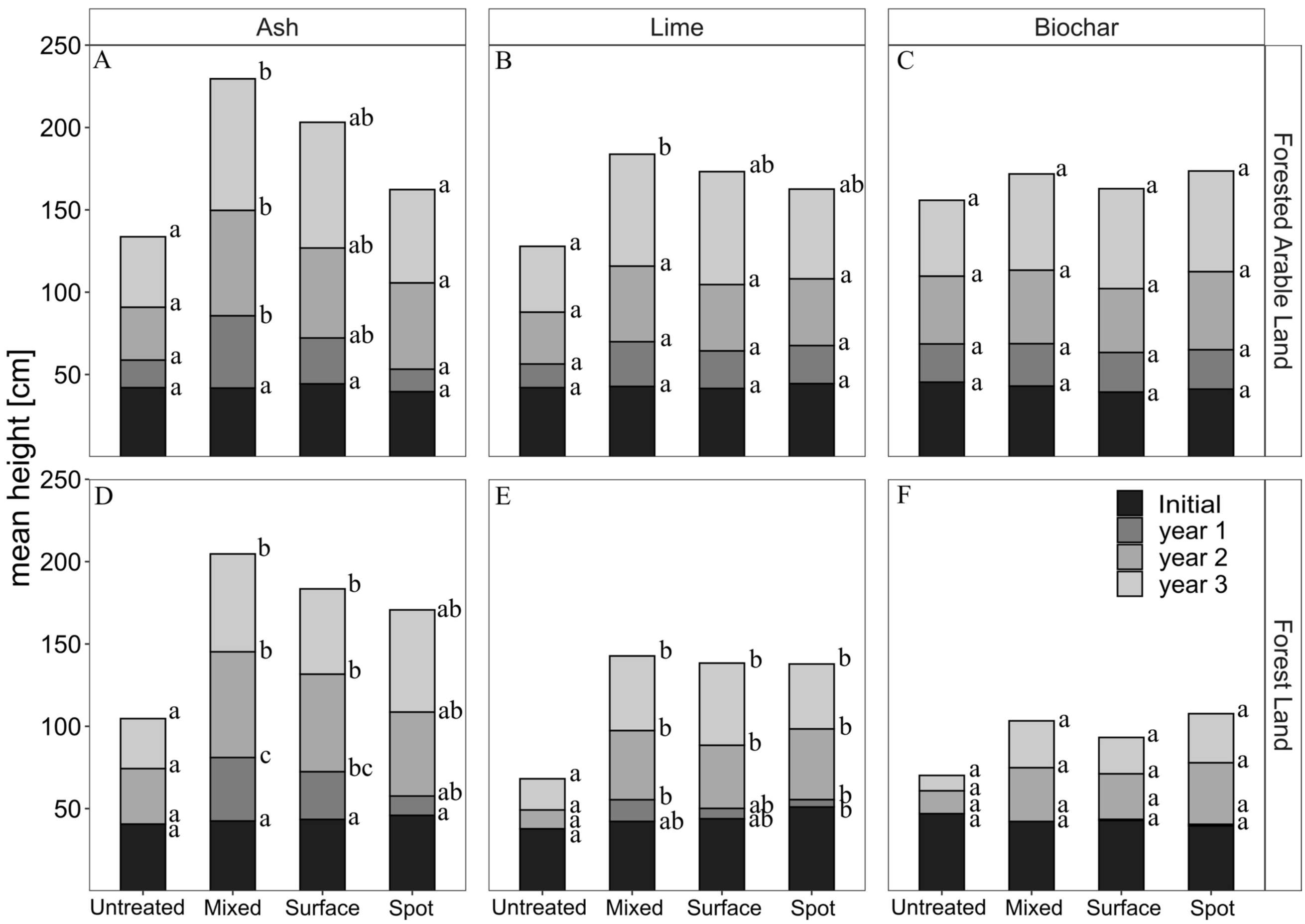

Fig. 2 Height growth at forested arable land (ArFor) **A** to **C** and forest land (For) **D** to **F**. Application of ash are shown in **A** and **D**, lime **B** and **E,** and biochar **C** and **F**. Letters indicate significant differences ($p \leq 0.05$) between the treatments within each year. Note that if a bar is missing, the corresponding yearly growth is too low to be shown

pH is sub-optimal for poplars, applying wood ash or lime may foster rapid growth and improve establishment.

Previous studies have found positive growth effects from biochar application on conifers, such as Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.), as well as on broadleaf species, including poplars, aspens (*Populus tremula* and *Populus tremuloides*), and silver birch (*Betula pendula*) [48, 67–70]. On the other hand, in other studies, biochar has shown limited growth effects on species such as poplar, alder, and willow [71, 72]. Ultimately, the growth impact of biochar varies heavily depending on application dosage, soil proprieties, and the biomass origin used for biochar production, highlighting the complex interactions between biochar type, soil properties, and plant growth [73, 74]. In this study, biochar derived from straw residues was applied, which may have been less effective in promoting poplar growth. Additionally, previous studies suggest that biochar's impact is enhanced when nutrient supplements are included [75–78], a factor not addressed in our experiment. These factors combined likely reduced the biochar's growth-promoting effects (Figs. 2C and F and 3C and F).

Previous studies have generally focused on either surface applications [28, 34, 79] or mixing the amendments into the soil during soil preparation [23, 30]. Interestingly, our results show only minor differences in growth and survival between the Mixed and Surface application methods (Tables 4 and 5, Figs. 2 and 3). Given prior research suggesting that surface applications might act more gradually on soil pH [26, 34] whereas mixing can yield immediate changes, one might anticipate greater effectiveness from the Mixed method. However, our findings indicate that both application methods can support poplar establishment at sites with sub-optimal conditions.

There are advantages and disadvantages associated with each of these methods. The Mixed method is more labor-intensive and requires application during soil preparation using specialized machinery to ensure cost efficiency. For this reason, technical development that integrates soil preparation with lime or wood ash application needs to be

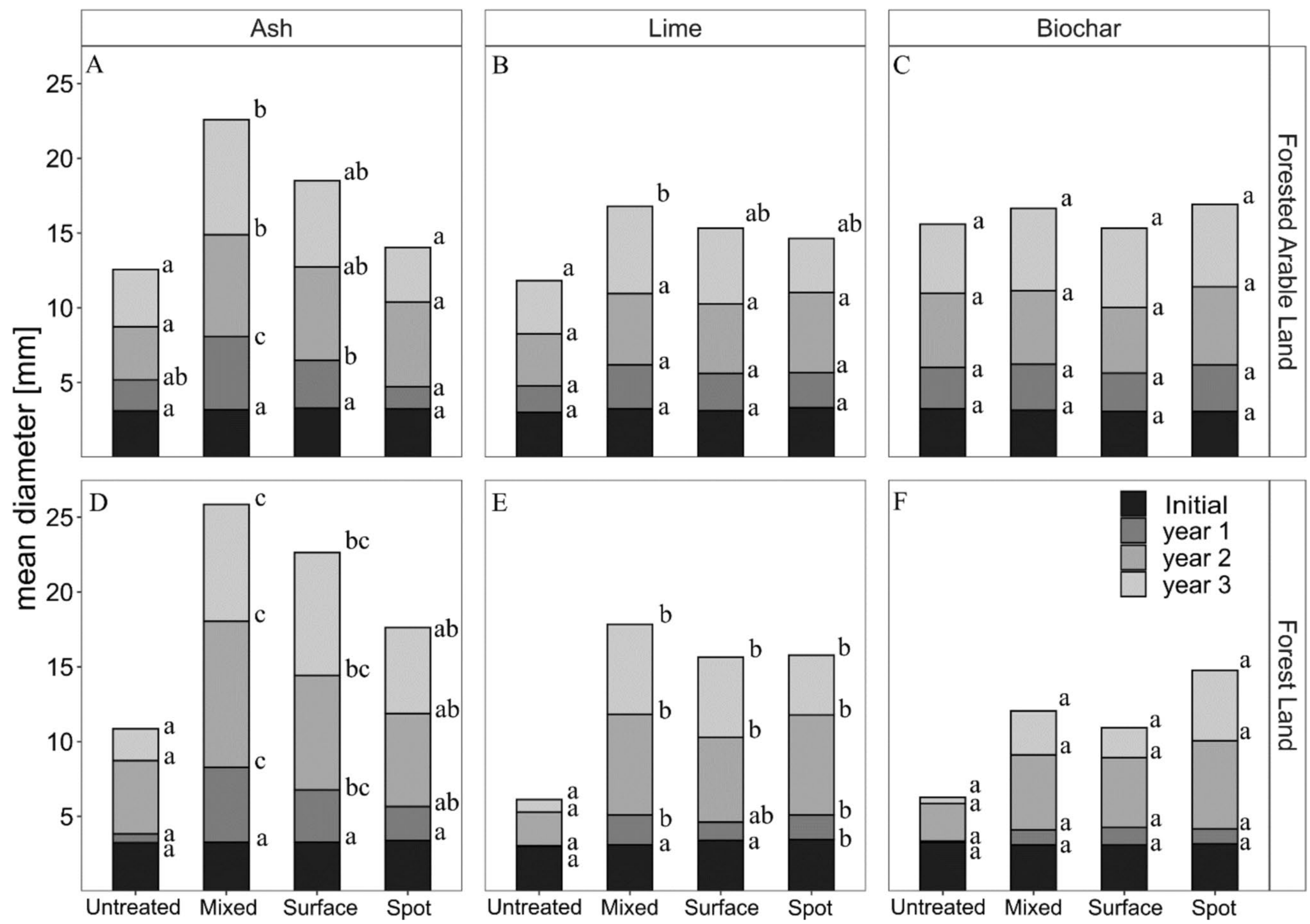

Fig. 3 Diameter growth at forested arable land (ArFor) **A** to **C** and forest land (For) **D** to **F**. Application of ash are shown in **A** and **D**, lime **B** and **E**, and biochar **C** and **F**. Letters indicate significant differences ($p \leq 0.05$) between the treatments within each year. Note that if a bar is missing, the corresponding yearly growth is too low to be shown

implemented. However, this method would require only one visit to the site. Conversely, the Surface method can utilize existing technology for application but currently requires two types of machinery: one for soil preparation and another for wood ash or lime application. An additional advantage of the Surface method is its ability to treat the entire planting area even at later stages of the rotation period, while the Mixed method can be applied only before planting. Moreover, the Surface method may be more versatile in treating sites with stones, potentially expanding areas suitable for poplar plantations compared to the Mixed method, which may be limited by its inefficiency in mixing wood ash or lime into soils containing large stones. Furthermore, advancements in drone applications within the agriculture and forestry fields might provide a low-effort and cost-effective way to apply wood ash or lime on the surface of the stands [80, 81].

Changes in soil pH are closely connected to the availability of macro- and micronutrients [82–84] but wood ash and lime can also influence soil fertility by addition of nutrients. There are though differences between the two compounds. Lime primarily adds calcium (Ca) and magnesium (Mg), whereas wood ash also provides phosphorus (P) and potassium (K), and micronutrients manganese (Mn), copper (Cu), molybdenum (Mo), and nickel (Ni) (Table 2). Indeed, at both our experimental site types (forest and forested arable sites), wood ash application increased P, K, Ca, Mg, Mn, and Zn levels and soil pH (Table 3), a result consistent with other studies [27, 39, 44, 85–87]. In fact, we do observe a higher growth with wood ash and that its effect spanned a broader pH and soil chemistry ranges (Fig. 4) indicating that these changes could be the reasons for wood ash increasing tree growth of poplars. It is important to note, however, that the growth effects of wood ash can vary considerably due to its variable composition [27, 88].

Low soil pH can impede plant growth by increasing the concentration of toxic metal ions, leading to stunted growth and plant mortality. Therefore, increasing soil pH through lime or wood ash application decreases the solubility of aluminum (Al^{3+}) and manganese (Mn^{3+}) ions, which are known

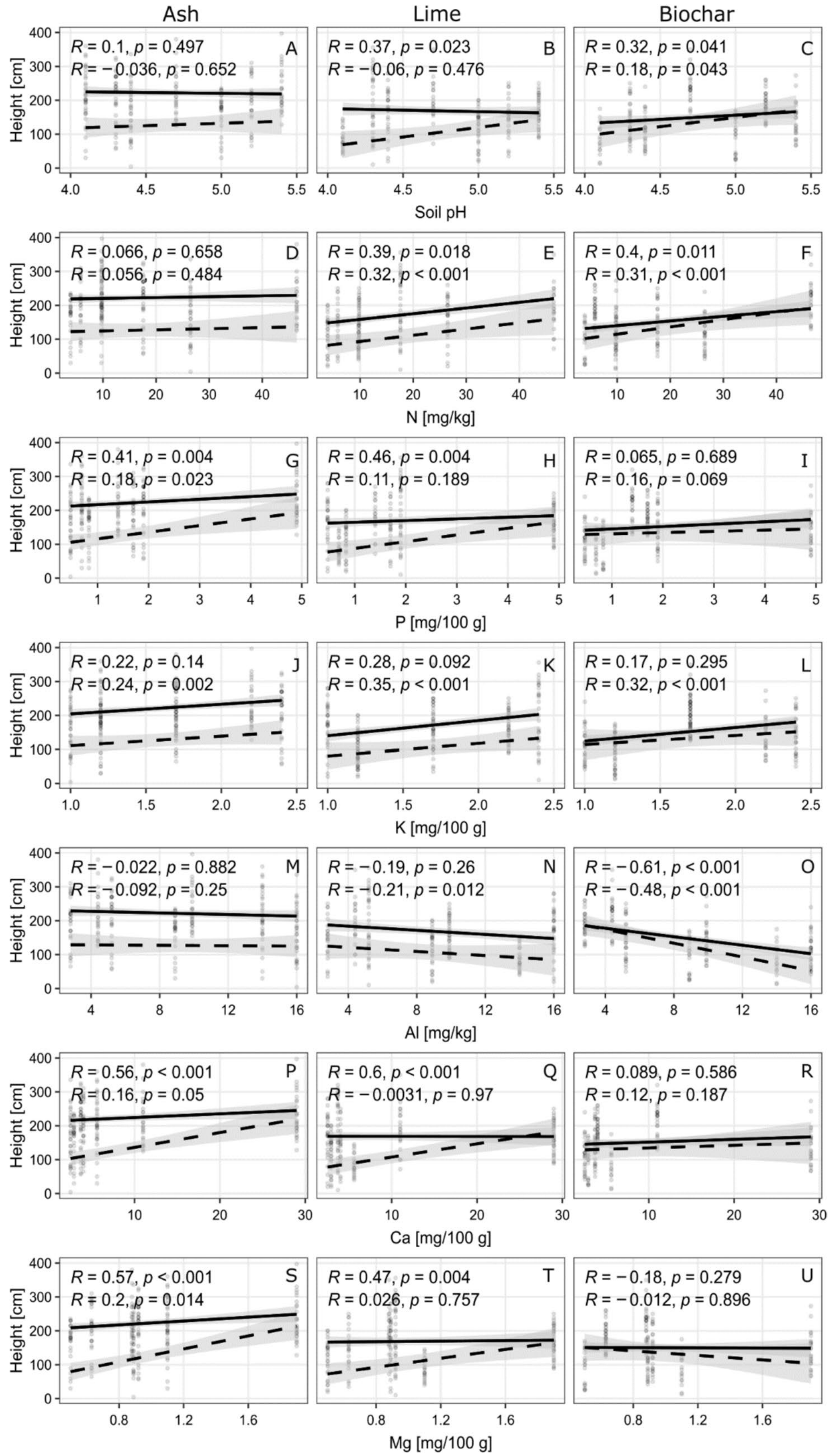

Fig. 4 Linear regression of tree height after three growing seasons vs. soil proprieties. A–**C** Soil pH with plants treated with **A** wood ash, **B** lime, and **C** biochar. **D**–**F** Total nitrogen (N) with plants treated with **D** wood ash, **E** lime, and **F** biochar. **G**–**I** Phosphorus (P) with plants treated with **G** wood ash, **H** lime, and **I** biochar. **J**–**L** potassium (K) with plants treated with **J** wood ash, **K** lime, and **L** biochar. **M**–**O** Aluminum (Al) with plants treated with **M** wood ash, **N** lime, and **O** biochar. **P**–**R** Calcium (Ca) with plants treated with **P** wood ash, **Q** lime, and **R** biochar. **S**–**U** Magnesium (Mg) with plants treated with **S** wood ash, **T** lime, and **U** biochar. The solid line represents plants treated with the respective soil amendment by the Mixed method, while the dashed line represents untreated plants. The *R*-value displayed at the top corresponds to the treated poplars (solid line), whereas the lower *R*-value represents the untreated poplars (dashed line). Confidence bands represent a 95% confidence interval

to inhibit root and shoot growth and increase mortality, particularly in Al^{3+} sensitive species like poplars [9, 89–92]. This toxicity reduction likely contributed to the improved growth we observed following lime and wood ash applications (Table 5, Figs. 2, 3, and 4).

Thus, the observed growth differences between wood ash and lime in our study likely originate from the combined effects of improved nutrient availability, nutrient supplementation, and the reduction of toxic metal ions, particularly crucial for early root development that has been shown to be of most importance for seedling establishment [52, 93]. While our study demonstrated elevated soil cation levels and base saturation (BS) after wood ash application (Table 3), the design did not allow us to determine the dominant factor driving growth improvements in poplar plantations on forest and forested arable land.

In our study, biochar showed a neutral (Figs. 2, 3, and 4) or positive (Table 5) effect on growth, though its increase was less pronounced than that observed with wood ash and lime. Biochar enhances plant growth by improving soil moisture retention and nutrient availability through reduced soil bulk density, increased fungal and microbial activity, and nutrient mineralization, while also mitigating toxic metal ion availability [45–47, 66, 94]. However, biochar has a longer residence time in soil compared to wood ash or lime, suggesting that while it has a slower direct impact on soil properties, its soil-improving effects may persist for decades or even centuries [95–97]. Given the rapid establishment needs of poplars, immediate soil condition changes are essential for optimal growth, especially in the early stages. The limited growth observed in our study suggests that biochar might not alter soil conditions quickly enough to benefit poplar seedlings within the timeframe of the study.

It should be noted that our soil analysis was designed to address spatial variability in soil properties within site [98, 99]. To account for this, our experiment incorporated multiple sampling points within each plot, thereby improving the reliability of the soil analyses. However, as the sampling was conducted 3 years after planting, potential temporal fluctuations in soil properties before and after treatments could not be assessed. Nevertheless, Simard et al. [100] found only minor changes in soil pH 2 years after clear-cutting, suggesting that temporal variations in soil pH may be relatively limited over comparable time periods.

In Sweden, poplar plantations on forested arable land are estimated to yield 4.5–6 Mg DW ha^{-1} $year^{-1}$ [2, 101] roughly 20% lower than those on arable land, where production averages around 8.4 Mg DW ha^{-1} $year^{-1}$. Our findings indicate that wood ash application can improve establishment and thus potentially increase biomass yields narrowing this production gap. Reduced mortality rates and improved growth in the early rotation phase are likely to contribute to higher biomass production at later stages, especially considering poplar need for rapid early growth to effectively establish, avoid competition, and withstand browsing pressure as a nutrient and water-demanding, pioneer species [61, 102]. However, our study covers only the first 3 years of the rotation period, leaving uncertainties regarding the long-term impact on total biomass production.

The establishment of large-scale poplar plantations on forested arable or forest land may face some regulatory constraints. For instance, Forest Stewardship Council (FSC) regulations limit the establishment of non-native species, like poplars, to 5% of forest land in Sweden. However, FSC guidelines permit non-native species to replace forest plantations, possibly classifying forested arable land as plantation forestry and thus allowing for poplar cultivation. Additionally, recent governmental recommendations in Sweden support planting broad-leaved species on such lands [103]. By contrast, poplar plantations on arable land are classified as energy crops and are not subject to FSC land-use restrictions, as these apply solely to forest lands.

This study's findings underscore the potential of wood ash as an amendment to increase biomass production from poplars on forested arable land, albeit with some regulatory and application considerations for maximizing its benefits.

Conclusions

Our investigation on the effects of wood ash, lime, and biochar applications on poplar growth at forested and forested arable sites offers valuable insights into how to enhance the establishment and the early growth of hybrid poplars in acidic soils in the temperate climate of northern Europe.

The results underscore wood ash's potential to improve poplar growth comparably to lime, suggesting a sustainable alternative for promoting poplar plantations on suboptimal sites. Furthermore, our findings indicate that applying wood ash or lime to the soil surface is as effective in promoting tree growth as mixing them into the soil. Such insights are critical for developing sustainable management practices for poplar plantations, contributing to biomass production and maximizing land utilization in areas unsuitable for food or feed production. Additionally, these results provide foundation for further research aimed at understanding the mechanisms underlying the impact of wood ash on poplar growth in suboptimal soil conditions.

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Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Luca Muraro and Henrik Böhlenius. The first draft of the manuscript was written by Luca Muraro and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analyzed during the current study are available in the supplementary material (S4).

Declarations

Competing Interests The authors declare no competing interests.

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