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Biochar in forestry

Status in the Nordic-Baltic countries

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Summary

This report summarizes the status of biochar in forestry in the Nordic-Baltic countries today. Biochar is charred material formed by pyrolysis of organic materials. In addition to improving soil physical and chemical properties and plant growth, biochar is a promising negative emission technology for storing carbon (C) in soils. The report gives an overview of current and potential uses, production methods and facilities, legislation, current and future research as well as biochar properties and effects.

Forests are both a source of feedstock for biochar production and a potential beneficiary for biochar use. Production is still limited in the Nordic-Baltic countries, but commercial production is on the rise and several enterprises are in the planning or start-up phase. In this report different biochar production technologies are described.

As the (modern) use of biochar for agricultural and especially forestry purposes is relatively new, in many countries there are no specific legislation regulating its use. Sometimes the use of biochar is regulated through more general laws and regulations on e.g. fertilizers or soil amendment. However, both inside and outside EU several documents and standards exist, listing recommended physical and chemical limit values for biochar.

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So far, most biochar studies have been conducted on agricultural soils, though research in the forestry sector is starting to emerge. The first biochar field experiments in boreal forests support that wood biochar promotes tree growth. Also, studies on the use of biochar as an additive to the growing medium in tree nurseries show promising results.

Because biochar C content is high, it is recalcitrant to decomposition, and application rates to soil can be high, biochar is a promising tool to enhance the C sequestration in boreal forests. However, available biomass and production costs may be barriers for the climate change mitigation potential of biochar. When it comes to effects on biodiversity, few field-based studies have been carried out. Some studies from the Nordic region show that biochar addition may affect microbial soil communities and vegetation, at least on a short time scale.

There is clearly a need for more research on the effects of biochar in forestry in the Nordic-Baltic region. Long-term effects of biochar on e.g., forest growth, biodiversity, soil carbon and climate change mitigation potential should be studied in existing and new field experiments.

Sammendrag

Denne rapporten oppsummerer status for biokull i skogbruk i de nordisk-baltiske landene. Biokull dannes gjennom pyrolyse av ulike typer organisk materiale. I tillegg til at tilsetning av biokull kan forbedre fysiske og kjemiske egenskaper ved jorda og øke plantenes vekst, er biokull en lovende negativ utslippsteknologi for å lagre karbon i jord. Rapporten gir en oversikt over nåværende og potensielle bruksområder, produksjonsmetoder og -anlegg, lovgiving, nåværende og framtidig forskning samt biokullets egenskaper og effekter.

Skog er både en kilde til råstoff for biokullproduksjon, og et potensielt marked for bruk av biokull. Produksjonen er foreløpig nokså begrenset i de nordisk-baltiske landene, men den kommersielle produksjonen er økende, og flere bedrifter er i planleggings- og oppstartsfasen. I rapporten beskrives ulike produksjonsteknologier for biokull.

Fordi bruken av biokull i moderne jordbruk og ikke minst i skogen er nokså nytt, finnes det i de fleste land ingen spesifikk lovgiving på området. Noen ganger reguleres bruken gjennom mer generelle lover og forskrifter, for eksempel gjennom regelverk som omhandler gjødselvarer og jordforbedring. Imidlertid finnes det både innenfor og utenfor EU ulike dokumenter og standarder som definerer anbefalte fysiske og kjemiske grenseverdier for biokull.

Hittil har det meste av forskningen på biokullets effekter på jord funnet sted innenfor jordbruket, men det begynner også å komme forskning innen skogbrukssektoren. De første feltforsøkene i boreal skog viser at tilførsel av biokull kan øke trærnes vekst. Også studier hvor biokull inngår som en del av vekstmediet i skogplanteproduksjon viser lovende resultater.

Fordi innholdet av karbon er høyt, karbonforbindelsene er motstandsdyktige mot nedbrytning og dosene som kan tilsettes jorda er høye, er biokull et lovende verktøy for å øke karbonbindingen i boreal skog. Mangel på tilgjengelig biomasse og høye produksjonskostnader kan imidlertid begrense biokullets potensial for å redusere klimaendringene. Når det gjelder effekter på biologisk mangfold, er det utført få feltforsøk. Noen studier fra Norden viser at tilsetning av biokull kan påvirke mikrobielle jordsamfunn og vegetasjon, i hvert fall på kort tidsskala.

Det er et stort behov for mer forskning på effektene av biokull i skogbruket i Norden og Baltikum. Langtidseffekter av biokull på blant annet skogens tilvekst, biologisk mangfold, jordkarbon og potensial for å redusere klimaendringer bør studeres i både eksisterende og nye felteksperimenter.

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Preface

This report summarizes the status of biochar in forestry in the Nordic-Baltic countries today: biochar production facilities and use, potential benefits and drawbacks, ongoing research and future research questions as well as existing legislation in the different countries. The report is written by the members of the SNS network "Biochar in forestry" 2022. The chapters on production facilities, legislation and ongoing research are mainly based on presentations given at our network workshop near Gardermoen, Norway, 15.-16 June 2022. In some of these fields, for instance production facilities and legislation, changes occur quickly. Interested readers are thus encouraged to seek updated information for the respective countries.

The following persons have had the main responsibility for the different chapters:

1. Introduction: Kjersti Holt Hanssen
2. Biochar production facilities: Kjersti Holt Hanssen
3. Current and potential products and uses: Kjersti Holt Hanssen, Jogeir Stokland
4. Legislation: Kjersti Holt Hanssen
5. Biochar properties and effects: Marjo Palviainen
6. Biochar production methods: Adam O'Toole
7. Effects on forest and seedling growth: Marjo Palviainen
8. Soil C stores and mitigation potential: Marjo Palviainen, Jogeir Stokland on "carbon credits"
9. Effects on biodiversity: Michael Gundale
10. Future research questions: Viktor J. Bruckman

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Ås, 23.02.23

Kjersti Holt Hanssen

Content

1 Introduction

Biochar is charred material formed by pyrolysis of organic materials. The feedstock is often based on organic residues such as wood chips, crop residue, or manure. Biochar is in many ways similar to charcoal but is not made to be burnt for energy generation, but for alternative environmental, agricultural and technical applications (EBC 2012-2022). The uses include soil amendment and water purification. In addition to improving soil physical and chemical properties and plant growth, biochar is a promising negative emission technology for storing carbon (C) in soils, as it is very resistant to degradation. IPCC credited biomass conversion to biochar as a promising negative emission technology in their 2018 report on Global Warming of 1.5 °C (http://www.ipcc.ch/report/sr15/).

The majority of biochar studies have so far been conducted on agricultural soils. However, in countries with large, forested areas, the use of biochar for soil amendment and for climate mitigation in forests are equally relevant. Biochar has been found to increase tree growth markedly in both pot experiments (Thomas and Gale 2015) and, recently, also in young forests (Grau-Andres et al. 2021, Palviainen et al. 2020). In addition, studies have shown that biochar may be used as a growth medium in forest nurseries, potentially reducing the use of peat (Köster et al. 2021). A review of biochar use in global forests, including the boreal zone context was recently published (Bruckman and Pumpanen, 2019).

Research on the use of biochar in forestry has now started to develop in the Nordic-Baltic countries, as the knowledge derived from agricultural studies cannot be directly transmitted to conditions found in forests. Present projects are looking into the effects of biochar on e.g., forest and seedling growth, soil carbon stores, soil respiration, nutrient cycling, nutrient leaching and biodiversity. Loading of biochar with fertilizers is another exciting path, with possible beneficial effects on forest growth and nutrient leaching. Additionally, production of biochar and biochar fertilizer products is developing in several Nordic-Baltic countries, often with feedstocks originating from forests.

In this new and emerging field of research, there is a need to sum up the present knowledge. The aim of the present report is to make a short summary of different aspects concerning biochar in forestry in the Nordic-Baltic countries; from production via legislation to effects of adding biochar on tree and seedling growth as well as on biodiversity and environment.

2 Biochar production facilities in the Nordic-Baltic countries

2.1 An industry in development

The commercial production of biochar is developing in several of the Nordic-Baltic countries. In Finland, there is an excess demand over supply for biochar. The production units range from small kilns at local farms or factories to larger industrial scale production. The following table is not exhaustive, but a current summary/overview based on the knowledge of the members of the “Biochar in Forestry” network.

Although torrefaction, hydrothermal carbonisation and coke production are carbonisation processes, the end products cannot however be called biochar under the definition of EBC (2012-2022). However, in the table below some examples of plants producing torrefacted wood is included. In those cases a comment is added about the end product.

Table 2.1. An overview of current biochar production in the Nordic-Baltic countries.

Country	Biochar plants	Production capacity	Comment
Denmark	Stiesdal SkyClean pilot plant (Skive, Jutland)		Inaugerated March 2022. Producing biochar, oil and gas, mostly from straw.
Estonia	Biolan biochar factory (Pärnu county, SW Estonia)	1700-1800 t/year	
	Baltania OÜ biochar factory (Jõgeva county, S Estonia)	160 000 t/year	Torrefaction technology
Finland	There is only a few producers, the largest being Carbofex (Tammerfors, S Finland)		In Finland, BC is mainly produced from wood-based biomass.
Latvia	Marienburg plant (NE Latvia)		Started production 2022
Lithuania	No biochar production facilites		Small amounts of biochar are produced in the laboratories of the Lithuanian Energy Institute and Vilnius Gediminas Technical University (VILNIUS TECH)
Norway	Oplandske bioenergi (Ringsaker, SE Norway)	1300-1400 m^3/year	Started production 2021
	Standard Bio (Telemark, SE Norway)	Potentially up to ca. 3000 m^3/year	

	Arbaflame/Treklyngen (Kongsvinger, SE Norway)	Up to 70 000 m^3/year	Pilot plant now in commercial production. Product closer to torrified wood.
	Biozin (Åmli, S Norway)		Still in planning phase. Bio based crude oil + biochar from forest feedstocks
	Several small facilities on farms, greenhouses, waste plants		
Sweden	Stockholm Biochar Project		A Pyreg reactor makes biochar from park and garden waste and the project has made innovative use of the biochar together with gravel as a growth substrate for urban trees
	Nordvästra Skånes Renhållnings AB		2022, VOW biogreen reactor will produce 1500 t/year biochar production from park and garden waste in Helsingborg
	EcoEra AB - Skånefrø		One of the largest biochar facilities located in Europe. Pyreg reactor.
	Hjelmsäter farm		Biomacon reactor to produce biochar for the farm and heat for the farm buildings

3 Current and potential uses of forest-derived biochar

Biochar properties - and thus its potential uses - varies with feedstock and production methods, as discussed in chapters 5 and 6. Likewise, the quality requirements will vary greatly with intended use. Biochar used as a feed additive in animal farming e.g. requires much stricter limit values for heavy metals and organic contaminants than if used as a cement additive (EBC 2012-2022).

Forests are both a feedstock source for biochar production and a potential market for biochar use. In the following, a short overview of different uses of forest-derived biochar is given, including use in forestry as well as in other sectors. Some of the uses are discussed in more detail in other chapters.

Soil conditioning

Biochar has a long history as a soil amendment agent, dating all the way back to the anthropogenic Terra Preta soil of the Amazonas (Mao et al. 2012). With its porous structure, biochar has many properties that can be good for soils with low organic content, including better soil aeration and aggregation. Biochar increases pH and water holding capacity and prevents nutrient loss through sorption (Bolan et al. 2022). By increasing pH, porosity, and water availability, biochars can create favourable conditions for root development and microbial activity (Joseph et al. 2021) while it suppresses plant pathogen activity (Bolan et al 2022). For degraded soils, biochar incorporation can improve soil physical properties, which in turn could potentially reduce runoff, erosion, and field waterlogging (Bayabil et al. 2015). Furthermore, biochar application increases water retention properties and increases plant available water content for all soil textures, especially for coarse-textured soils (Razzaghi et al. 2020, Edeh et al. 2020).

The effect on plant growth varies, with best effects on low-nutrient acidic soils and in sandy, dry soils (Biederman et al, 2013, Joseph et al. 2021). Research from Norway and the Nordic countries generally show a modest positive effect on agricultural soil quality, and no effect on plant yield when untreated biochar was added to arable land (O'Toole et al. 2022). Studies in Estonia show that biochar is a soil improver whose positive effect on crops lies in its ability to improve plant nutritional conditions by neutralising soil acidity, improving soil aeration, increasing soil fertility, and improving moisture content and cation uptake capacity, but impact on yields is neutral (Raave 2014). Soils with biochar have lower N_2O emissions and NH_4-N, NO_3-N and P leaching (Raave et al. 2014a). Varul et al (2011) showed that biochar may have a positive impact on seed germination and fertilizer efficiency.

In Estonian conditions, where the soil carbon balance is negative, biochar could be used to increase and stabilize soil C content (Raave 2014). Biochar could also be useful for in nitrate-sensitive areas, where it could help to retain nutrients in the soil and thus protect of groundwater.

Most studies on plant growth have so far been conducted on agricultural soils. However, also field experiments with tree seedlings and forests are now emerging, sometimes showing promising positive effects. See chapter 8 for a summary of effects on seedlings and forests.

Fertilizer

Biochar contains some nutrients and can also be used as a carrier for additional inorganic fertilizers. Nutrient concentrations vary a lot, depending on the feedstock and the conditions under which they are produced (see also chapter 5.2). Nitrogen, which is the most important nutrient in forest fertilization in the Nordic-Baltic countries, is partly volatilized during heating, while other nutrients become concentrated in the remaining biochar. Most of the biochar nutrients are not in a readily available form for plants, and the positive plant growth responses after biochar addition cannot be directly attributed to the nutrient content of the biochars but instead to the indirect effects of biochar in soil such as increased microbial activity and improved soil nutrient and water retention capacity (Lehmann and Joseph 2012).

Even though biochar studies are relatively scarce in Nordic-Baltic forest research, there is a strong tradition of documenting tree growth responses to fertilization. Nutrient availability, especially nitrogen, is a limiting factor for tree growth in most coniferous boreal forests, and experiments have shown that a single forest fertilization with ca. 150 kg N ha^{-1} leads to a growth increase of around 15 m^3 over a 10-year period (Ingerslev et al. 2001). However, nitrogen leaching is a concern, and fertilization might also have implications for biodiversity (Hedwall et al. 2014). Using biochar as a nitrogen carrier by loading the biochar with N has potential to reduce leaching and other environmental effects through slow release of nutrients. Additionally, it can improve the N use efficiency of fertilization (Gao et al. 2022). Biochar incorporated in the topsoil layer of the forest floor may also reduce the “nitrogen flush” effect; i.e. increased leaching rates after rapid decomposition of inherent soil organic matter following logging operations. In agriculture, a body of literature is turning up on the use of biochar as an environmentally friendly carrier for N as fertilizer, but in forest research this topic is only starting to emerge.

Carbon storage

Biochar has a high content of carbon and is recalcitrant to decomposition. In addition, application rates to soil can be high, thus adding biochar to agricultural or forest soil is a potential tool for C sequestration and climate change mitigation. See chapter 8 for a discussion of the climate mitigation potential of biochar.

Urban forestry and community gardening

Trees planted in an urban environment face challenges related to limited availability of water and oxygen to tree roots. Biochar has properties that may relieve some of the stress to urban trees, when mixed in with gravel and other soil amendments in the planting bed. A main advantage of biochar for urban planting is that it resists compression and compaction, which is seen as one of the biggest threats for trees and other perennials in urban parks and streets (Embrén 2016). Adding biochar to the soil has shown to improve nutrient and water availability for urban trees and enhance growth (Lo Piccolo et al. 2022, Kopakkala 2022). In addition, it was shown that biochar reduces negative effects of salt stress (Akhtar et al. 2015) which may be induced along roads by de-icing operations during winter months.

Incorporating biochar as a growth medium within building structures has the advantage of its relatively low weight, and hence there are numerous examples of including green spaces in the urban context by using biochar, e.g. in Southeast Asia (Bruckman et al. 2016).

The use of biochar for soil conditioning is increasing in urban environments where the usage has expanded to community gardening. The increasing use of biochar combined with tree planting and community gardening has also initated biochar production in some Nordic urban areas, including Stockholm and Sandnes/Norway (Milestad 2020, Rassat 2020).

At present, the use of biochar for urban tree planting constitutes a relatively stable and reliable market for some producers (Prestvik and Lilleby 2021, E. Stuve, Oplandske bioenergi, pers. comm.)

Animal farming

Biochar can be used as a feed additive or supplement to domestic animals to increase animal health, reduce enteric methane emissions and increase meat and milk productivity (Schmidt 2012, Bolan et al. 2022), though positive effects e.g. on productivity or methane emissions are not always found (Lind et al. 2022). Activated carbon and biochar can absorb toxic substances and harmful germs from the digestive system and have a regulative effect on digestion (Schmidt et al. 2019). Research has been carried out on animals like dairy cows, cattle, poultry, sheep, goats and pigs (Bolan et al. 2022). Biochar fed to animals must be of high quality (EBC 2012-2022).

Using biochar as a feed additive also affects the animal manure. In an incubation trial Romero et al. (2022) found that the carbon in biochar changes minimally going through the digestive tract of ruminants. They observed that manure from cows fed with biochar had a higher availability of nitrogen compared to ordinary manure. No influence was found on emissions of CO_2, N_2O and CH_4 when soil was fertilized with incubated manure enriched with biochar. The addition of biochar to liquid manure could reduce NH_3 emissions (Raave et al. 2014b).

Adding biochar to litter has potential to reduce moisture and pathogens (O'Toole et al. 2022, Schmidt et al. 2019).

Composting

Biochar has been investigated as a mixture in compost to improve the composting process and increase the quality of the final product, as it is a stable structural material with properties that can affect oxygen conditions, pH and humidity (O'Toole et al. 2022). Adding biochar to the compost can reduce the production of N_2O, CH_4 and CO_2 and reduce N loss (Agyarko-Mintah et al. 2017, Awashti et al. 2017, Chen et al. 2017), increase pH, reduce bioavailability of heavy metals and improve the humification of the end product (Awashti et al. 2017, O'Toole et al. 2022).

Decontamination

Several studies suggest that biochar is suitable for immobilising organic contaminants in both soil and water (Ahmad et al. 2014). This is due to a highly aromatic nature, rich surface functional groups, micro-porotic surface, and high specific surface area (Bolan et al. 2022). Also, potentially toxic elements like heavy metals can be immobilised by biochar and reduce the uptake by plants (Joseph et al. 2021). The main mechanisms of biochar interactions with toxic elements include electrostatic attraction, ion exchange, and complexation with functional groups on the surface of biochar. The immobilisation efficiency depends on the feedstock raw material, biochar dose, conditions during pyrolysis, element type, and soil properties (Bolan et al. 2022, Haider et al. 2022). Based on these properties, biochar can be used as a soil additive for remediation of contaminated soils as well as for (waste) water treatment.

The area of soil decontamination requires systems thinking and assessment, as it usually requires long-term strategies. It may be advisable to include combined perspectives of agriculture and forestry in directional or circular biochar application. In larger contexts, industrial mining of heavy metals/contaminants from biochar produced from contaminated feedstock can be a future strategy, in addition to immobilization (Sohi & Kuppens 2016).

Recent studies also show that biochar itself can contain contaminants like polycyclic aromatic hydrocarbons and heavy metals. Especially the feedstock and pyrolysis temperature affect the content of contaminants. Biochars obtained from plant substrates usually have a much lower content of contaminants compared to biochars produced from sewage sludge or animal manure, and their toxicity is lower (Godlewska et al. 2021). Thus, even though the application of biochar in soils usually does not have a toxic effect and even results in a range of desired effects, using the right quality according to intended use is important.

Construction

Biochar can be added to concrete, mortars or other types of composites or plasters (Bolan et al. 2022, Legan et al. 2022). The latter review found that biochar dosages in studies ranged from 0.5% to 40% and that in most composites, the addition of biochar increased strength and reduced thermal conductivity and bulk density of fresh mortars. Adding biochar to building materials also has a potential for carbon footprint reduction.

Other industrial uses

Biochar shows versatile physicochemical properties and can have a wide applicability in a range of fields (Xie et al. 2022). Owing to a high surface area, pore structure, and suitable surface chemistry biochar can be used in air filters to remove volatile organic compounds (Bolan et al. 2022, Vikrant et al. 2020). Biochar can be used as a catalyst in various chemical processes (Lee et al. 2017). In metallurgic as well as other types of industry, charcoal is used as a reducing agent, as a promising alternative to conventional fossil reductants (Xie et al. 2022). Using biochar as a substitute will greatly reduce the carbon footprint (Suopajärvi et al. 2013).

4 Legislation on biochar in forestry in the Nordic-Baltic countries

4.1 Legislation

As the use of biochar for agricultural and especially forestry purposes is relatively new, in many countries there are no specific legislation regulating its use. The use of biochar may be regulated through more general laws and regulations on fertilizers, soil amendment or compost, though sometimes it is not clarified as to whether these regulations apply in forests or not. In agriculture there are ususally regulations concerning limit values of e.g. heavy metals or organic pollutants, but again it is often unclear whether the same limits will apply for the use of biochar in forests. Table 4.1. gives an overview of the current (lack of) legislation in the field.

However, an updated fertilizer regulation in EU from 16 June 2022 will allow biochar to be a component in EU certified fertilizers and soil improvers to be traded across the union (Anon. 2022).

In addition, both inside and outside the EU several documents and standards exist, listing recommended physical and chemical limit values for biochar (see chapter 4.2).

Table 4.1. Overview of the current legislation on biochar in forestry in the Nordic-Baltic countries.

Country	Legislation status
Denmark	There are no formal regulation for the use of biochar, unlike for e.g. bioash and sewage sludge.
Estonia	There are no specific regulations on biochar yet.
Finland	Currently there are no regulations concerning biochar, while that does not significantly limit the overall development of the biochar market. Main legislative barriers are that commercialization of pyrolysis liquids require authorisation, and that certain biochar enrichment processes might be affected and limited by the fertilizer legislation.
Latvia	Biochar is not mentioned in the regulations concerning fertilizers etc. The law does not affect their use for fertilisation.
Lithuania	No specific legistlation in the agriculture and forestry sectors.
Norway	No specific legislation on the use of biochar in forestry. In general, the use of organic fertilizers and products for soil amendment is regulated through “Regulation on Fertilizers etc. of Organic Origin" (https://lovdata.no/dokument/SF/forskrift/2003-07-04-951). It does not define forest as one of the land use types that can be fertilised by e.g. ash, and biochar is not mentioned at all. The Norwegian Food Authority thus lay down that biochar, like ash, cannot be spread in forests without special permission (E.M. Røsås, pers. comm. 2022)
Sweden	No specific regulation on biochar amendment

4.2 Biochar standards

To set standards for the production and quality of biochar, several initiatives have been launced the last decade. The standards have partly been initiated due to the "regulatory gap" that has existed in the biochar area up till now (Meyer et al. 2017). They are general standards or certificates, not applying to forestry use in particular. They define key properties of biochar (moisture content, total ash content, N and C content, pH-value, electrical conductivity, particle size etc) while setting limits for toxicants like heavy metals or organic pollutants. To a varying degree they also define or evaluate the sustainability of the feedstock used and the production process.

The **European Biochar Certificate** (EBC) is one of these. At present, EBC is a voluntary industry standard in Europe, except for Switzerland where it is obligatory for biochar sold for agricultural use. According to the EBC homepage (https://www.european-biochar.org), it was introduced "to provide customers with a reliable quality standard, while giving producers the opportunity to prove that their products meet well-defined and recognized quality standards. It further aims to provide a firm state-of-the-art knowledge transfer as a sound basis for future legislation".

The **IBI Biochar Standards** and IBI Certification programme is another standard, offered by the International Biochar Initiative (https://biochar-international.org/characterizationstandard/). This is a US initiative inteded to be used internationally. According to the website, the standard "provides the tools needed to universally and consistently define what biochar is, and to confirm that a product intended for sale or use as biochar possesses the necessary characteristics for safe use".

Finally, the British **Biochar Quality Mandate** (BQM) is a UK-specific initiative that was initiated in 2011, the first version released in 2014 (Shackley et al. 2014). The evaluation of the sustainability of feedstocks is an important feature of the BQM. It draws upon EBC and IBI in specifying limits for toxicants as well as key properties of biochar (Meyer et al 2017).

In Meyer et al. (2017) these three standards/certificates are presented and discussed.

5 Biochar feedstocks, properties and effects

5.1 Biochar feedstocks from forestry

Biochar can be made from almost any type of biomass, including agricultural and forestry waste products, municipal waste, green and food waste (Ippolito et al. 2020). Typically, biochar from woody residues shows the best performance for soil conditioning. Feedstocks from forests and forestry may include wood chips and shavings from almost any tree species or tree part. However, in a circular economy a cascade use of resources is optimal (Navare et al. 2022), and most biomass feedstock compete with other demands (Hagenbo et al. 2022). Thus, from a sustainable point of view as well as an economic one, different types of secondary biomass or residues from harvesting or wood processing may be considered the best potential feedstocks for biochar, under the constraint that additional removal of biomass has no negative effects on site productivity and biodiversity. Such biomass includes harvest residues (branches and tops), small dimension wood, bark and sawdust.

The potential amount of biochar feedstocks from forestry may be substantial. Bosch et al. (2022) estimated a total of 130 mill. m^3 wood chips (all grades) and bark per year available in Europe, given the present harvesting level. Hagenbo et al. (2022) estimated that in Norway, the feedstock supply of forest harvest residues for biochar production to be 0.8 mill. tons in 2020, increasing to 1.2 mill. tons in 2120.

Research on the potential amount of biomass in the form of small dimension wood in the forest undergrowth shows that there are considerable reserves available. Indriksons et al. (2020) obtained that in Latvian drained forests, comprising about 30% of the land's forest area, there are on average 4.76 t ha^{-1} and totally 6.26 mill. tons of dry wood mass available. Recalculated to biochar outcome it would give 1.76 t ha^{-1} and 2.19 mill. tons respectively.

Even though reserves of low-competitive forest biomass exist, the use of biochar for climate mitigation and other uses are currently restricted by the availability of biomass and the costs of both biomass and the finished product (Fuss et al. 2018, Hagenbo et al. 2022, O'Toole et al. 2022).

5.2 Biochar properties and effects

The biochar structure and properties depend on feedstock, pyrolysis temperature, heating rate and the time the material is held at a given temperature (Lehmann and Joseph 2012, Sun et al. 2014, Bruckman and Pumpanen 2019, Ippolito et al. 2020). Biochar is C-rich material and its C content is generally >60%. Majority of biochar C is aromatic. The aromatic ring structures increase the recalcitrance of biochar against decomposition, and therefore, biochar exists in the soil for hundreds or thousands of years (Lehmann and Joseph 2012, Ippolito et al. 2020). As the pyrolysis temperature increases, the aromatic C structure increases.

Biochar nutrient concentrations are extremely variable depending on the feedstock and the pyrolysis conditions under which they are produced (Lehmann and Joseph 2012, Ippolito et al. 2020). Some nutrients such as nitrogen partly volatilize during heating, while other nutrients become concentrated in the remaining biochar. Most of the biochar nutrients are not readily available form for plants, and the positive plant growth responses after biochar addition cannot be directly attributed to the nutrient content of the biochars but instead to the indirect effects of biochar in soil such as increased microbial activity and improved soil nutrient and water retention capacity (Lehmann and Joseph 2012).

Biochar is a porous material. The specific surface area of biochar is high, up to 600 $m^2 g^{-1}$, and increases as pyrolysis temperature increases within a certain range (Lehmann and Joseph 2012, Weber and Quicker 2018). At low temperatures volatiles and tars fill the internal pore structure of biochar which reduces the surface area. As the temperature increases, these substances decompose into volatile gases which reduces the pore size but increases the number of pores in the biochar, resulting in more microporous structures and larger surface area. At very high temperatures, the surface area can decrease probably due to the destruction of microporous structure and the enlargement of micropores. A large surface area is connected to biochar cation exchange capacity (CEC) and water holding capacity (Lehmann and Joseph 2012).

Biochar contains functional groups such as hydroxyl, carboxyl and carbonyl groups (Lehmann and Joseph 2012, Weber and Quicker 2018). The number and density of functional groups decrease as the pyrolysis temperature increases. In the pyrolysis process, hydroxyl, carboxyl and carbonyl are retained due to the incomplete decomposition of cellulose which increases the CEC of biochar. Within a certain range, the biochar CEC decreases with increasing temperature, accompanied by the destruction of oxygen-containing functional groups, the reduction of the negative charge on the biochar surface, and the decrease in the O/C ratio.

Most of functional groups are oxygen-containing or alkaline, these provide biochar with good absorption ability and ion exchange capacity. These properties can be utilized in alleviating environmental pollution. The biochar has been used in soil remediation and water purification (Qiu et al. 2022). Biochar produced at relatively high pyrolysis temperatures can generally effectively manage organic pollutants via increasing surface area, hydrophobicity and microporosity, whereas biochar generated at lower temperatures is suitable for removing polar organic and inorganic pollutants through oxygen containing functional groups, precipitation and electrostatic attraction (Qiu et al. 2022). Wood biochar has been shown to effectively adsorb ammonium, nitrate and organic nitrogen, phosphorus and metals from forest runoff waters (Kakaei Lafdani et al. 2020, 2021, Saarela et al. 2020, Kinnunen et al. 2021). The adsorption of nitrogen has been shown to increase with increasing water nitrogen concentration (Kakaei Lafdani et al. 2021). The adsorption is a rapid process which suggests that a biochar can effectively adsorb nutrients even with low water residence time, given that the nutrient concentration in water is sufficiently high (Kakaei Lafdani et al. 2020, 2021, Saarela et al. 2020). Thus, biochar is a promising water protection tool in forestry, especially in sites where there is a risk of a high rate of nutrient export after forest harvesting or drainage.

Biochar is alkaline, this is related to the carbonates, phosphates, and ash formed during pyrolysis (Ippolito et al. 2020). The pH increases as the pyrolysis temperature rises due to the decomposition of acidic functional groups such as carboxyl and phenolic hydroxyl, and the volatilization of organic acids. Thus, the application of biochar can alleviate soil acidity.

Biochar bulk density is lower than soil bulk density (Blanco-Canqui 2017). Consequently, biochar application reduces soil bulk density, and more so in coarse-textured than in fine-textured soils (Blanco-Canqui 2017). Biochar application increases also soil porosity by reducing soil bulk density and by increasing soil aggregation (Lehmann and Joseph 2012, Blanco-Canqui 2017). The increased soil porosity improves the movement of water, heat, and gases in the soil which may have positive effects on plant growth.

The physical and chemical properties of biochar affect several functional roles that they may play in environmental management applications. Biochars with different properties can be developed for different environment applications by selecting raw material and regulating production conditions (Sun et al. 2014, Qiu et al. 2022). In the future, it would be important to study how physical and chemical properties of different biochars change in soil over time and how these changes influence their function.

6 Biochar production methods

Biochar production technology can be categorized in terms of method, automation, portability, biochar vs energy input, and suitability to specific feedstocks. Broadly speaking biochar is made either via a **batch process** where a feedstock is loaded and biochar is unloaded manually, or a **continuous process** where chipped, pelletized or granular material is fed in and out of a reactor. Batch technologies have a lower investment cost than continuous technologies because they do not usually require power or automation equipment. However, batch technology requires higher labour input and are more difficult to extract usable energy from because of the intermittent nature of a batch process.

Pyrolysis and gasification are the main methods for producing biochar. Pyrolysis is the heating of biomass in the absence of O2, and gasification involves controlled input of O2. Biochar production in a pyrolysis reactor requires the use of external energy to preheat the reactor. Gasification can sacrifice some of the biomass in order to create the heat required to gasify the rest of the feedstock. Large scale gasification can be used to produce electricity or liquid biofuels (O'Toole and Grønlund, 2012). A pyrolysis reactor usually yields between 25-35% biochar, and gasification reactors (due to the partial oxidation of char) yield approximately 10-25% biochar. Biochar yield decreases at higher pyrolysis temperatures however carbon stability is greater at higher tempeatures. The decision on which reactor to choose will depend on whether the business case requires more energy products or biochar. Biochar can also be produced from incomplete combustion in traditional biomass boilers, but there has not been a practice until now in separating out ash from unburnt biochar.

6.1 An overview of Biochar production technologies

An important consideration for production of biochar from forestry residues is whether to bring the feedstock to the technology or whether to bring the technology to the feedstock. There exist many forest harvest locations within the Nordic region which are remote and a significant distance to nearby cities where biomass could be used for district heating. There are also many situations where biomass harvesting is a one-off occurrence, such as in the clearing of forest for building of transport and industrial infrastructure. In such circumstance, a portable technology which can convert biomass to biochar on-site may be more relevant. A life-cycle analysis could identify whether a decentralized or centralized biochar strategy is more environmentally sustainable. See Anderson et al. (2016) for an LCA approach in (forest) biochar systems with a focus on North America.

The following is a selection of commercially available technologies for the production of biochar.

6.1.1 Open top mobile incinerators and gasifiers with biochar recovery

Tigercat 6050 Carbornator from Tigercat (USA): This machine is able to carbonize whole logs, branch and forestry debris. Biomass is loaded up into the open top carbonizer where it is burnt at high temperatures with the aid of high-speed fans. If biochar and not ash is desired, the biochar must be quenched with water and then a bottom feeding auger continuously removes the biochar from the reactor. Because of the high temperatures and excess of O2 which is used the biochar yield is often as low as 10%, but because of the volume of material being processed it can still result in a significant amount of biochar being produced in a work shift. A limiting factor for the use of this technology at remote forestry sites is whether water is available for quenching the outgoing char. The unit is currently being used around the world at waste processing facilities where large amounts of demolition wood waste is available.

Fig. 6.1. Tigercat 6050 Carbonator. Photo: www.tigercat.com

EnviroSaver 350 Air Curtain Carbonizer from ROI equipment (USA): This unit is similar in design to the Tigercat as described above where unchipped woody biomass can be loaded with an excavator into the open top carbonizer. High temperatures and high speed fans are used to burn fresh biomass with moderate to high moisture content with relatively low emissions. (See: https://roi-equipment.com/wp-content/uploads/2018/07/350-spec-sheet.pdf)

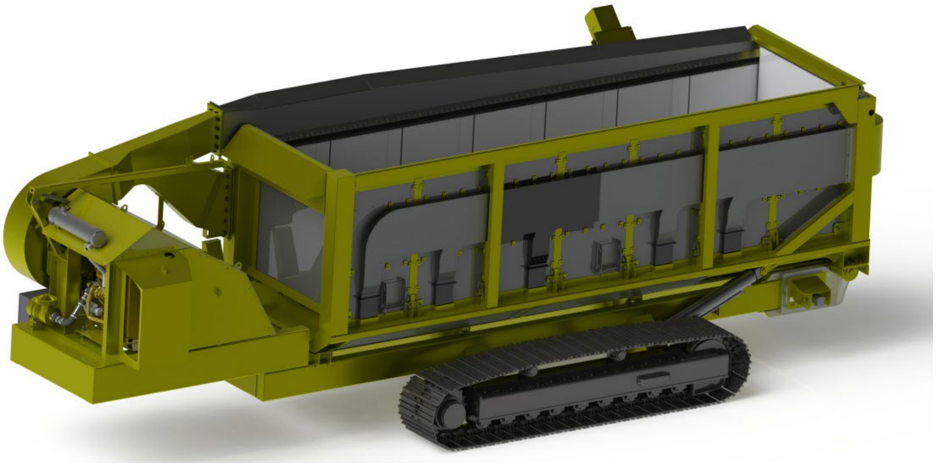

Fig. 6.2. Envirosaver 350 from ROI Equipment

Charboss from Airburners Inc.: For smaller scale on-site conversion the Charboss is a reactor which burns unchipped residues in the same manner as the Tigercat and the Envirosaver, but is a smaller unit and has a trailer fitting and wheels such that it can be towed by a vehicle. It has an automatic discharge of biochar at the bottom of the reactor via a stainless steel belt conveyor, and a shallow water pool can be located at the discharge point to quench the outgoing char. The Charboss has been used in a number of US forestry service projects for the processing of invasive species brush.

It has the advantage that it can be easily towed and manoeuvred into areas where the biomass is located. (see: www.airburners.com)

Fig. 6.3. Charboss from Airburners Inc. (photo credit: www.airburners.com)

Kontiki kiln

For smaller scale operations and where a lower budget is a restraint the Kontiki kiln could be a good option for processing forestry residues. A Kontiki kiln has an open top and operates on the "flame cap" principle where newly loaded biomass combusts on the top of the pile, thereby consuming oxygen in the "flame cap" and conserving the biochar further down in the pile from oxidation. The method requires considerable skill of the operator to understand when to add more biomass and to select twigs and branches that are dry and are not too thick. The cone shape of the kiln creates a vortex air flow where incoming air at the top of the reactor pulls smoke into the middle of the fire where it is burnt. The design allows for lower emission biochar production compared to open pile burning of biomass. Kontiki kilns are often fitted with a water connection point at the bottom such that the char can be quenched from below. Like all of the open top reactors, the Kontiki has the benefit that there is no chipping required. However, the diameter of branches should be ideally under 2 cm such that the carbonization progresses quickly and that there is no uncarbonized material left at the end of the burn. The kontiki kiln is an open-source design and several companies around the world have innovated different versions to cater for the needs of hobby and small-scale farmers, as can be seen from the "stretch" Kontiki kiln featured in Fig. 6.4.

Fig. 6.4. 1850 Liter Kontiki Stretch kiln from Terra preta Developments in Tasmania Australia. Biochar is grinded to a finer particle size using a 6 hp garden shredder. Photo: www.terrapretadevelopments.com.au

6.1.2 Batch retorts

Batch retorts are closed reactors where there is more exclusion of oxygen from the reactor. The reactor needs to be filled at the start and emptied at the end of the carbonizing/pyrolysing process. Batch retorts have traditionally been used for small scale production of charcoal in developing countries for the BBQ charcoal market. We do not provide a review of the traditional batch kilns but rather focus on batch units which can either produce biochar from larger amounts of forestry residue or where the reactor includes an energy recovery component.

CharMaker Mobile Pyrolysis Plant (MPP) from Earth Systems Pty Ltd (Australia)

This batch reactor is built within a standard shipping container and can be delivered by truck to the location where the biomass is located. Whole logs and branches are loaded firstly into cages which are then loaded into the reactor. Batch processing of 13 and 30 m3 of forestry residues per batch is achievable when using either the 20 ft or 40 ft biochar reactors. An onboard computer controls the ignition and fan operation and optimizes the process for low emissions under operation. (see: https://www.esenergy.com.au/charmaker-2)

Fig. 6.5. Charmaker MPP from Earth Systems Pty Ltd (Australia) Photo: esenergy.com.au

6.1.3 Continuous biochar production reactors

There are numerous continuous biochar production reactors now available on the market. What they often have in common is that the feedstock is reduced into a suitably size that it can be fed into a hot reactor and where biochar is produced, usually as a co-product to energy outputs including: heat, liquid biofuel, and/or syngas. Due to the energy recovery component continuous reactors are more likely to be stationed in a permanent location and where other biomass handling infrastructure is integrated e.g. wood chip grinding, driers for incoming biomass, heat exchangers and biochar packing facilities. Due to their greater complexity, continuous units are much more expensive than batch units. The following is a selection of continuous reactors available in the market anno 2022.

Biogreen reactor from VOW ASA (Norway)

This is a continuous reactor which uses electricity to heat up an internal auger which both transports and heats biomass particles at the same time. Pyrolysis syngas can be collected, and once cleaned be used to run an electric motor. The biogreen reactor was selected in 2022 for a biochar research facility in Sweden (See: https://www.biogreen-energy.com)

Fig. 6.6. Biogreen reactor. Photo: biogreen-energy.com

Pyreg Gmbh

The Pyreg reactor is a slow pyrolysis auger reactor which can process wood chips or even dried sewage sludge. Produced syngas are burnt completely in a FLOX™ reactor, and resulting hot gasses are fed back to indirectly heat the reactor and the biomass within it. Excess heat can be captured via a heat exchanger for drying or district heat applications. The Pyreg reactor was selected for the facility at JordPro AS in Trondheim, Stockholm biochar project, and Skånefrø AB in Southern Sweden

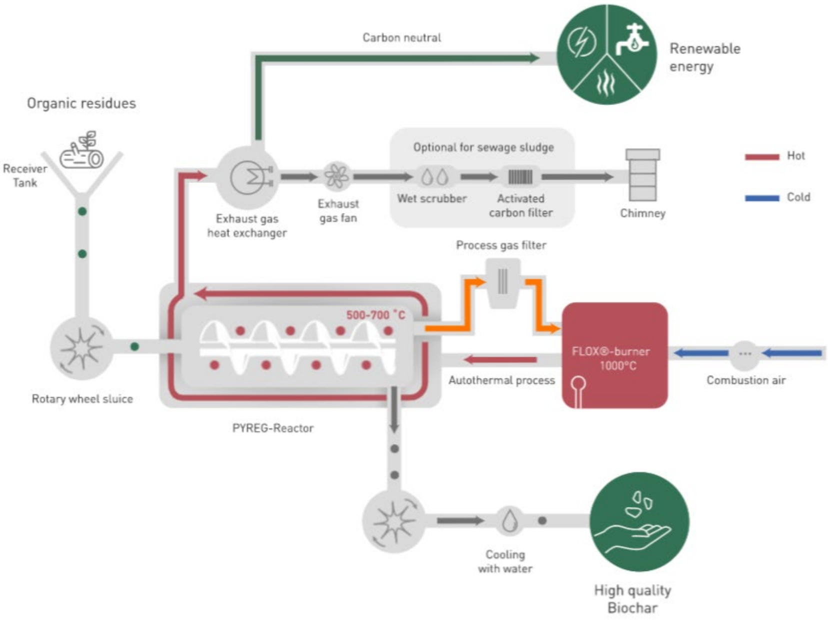

Fig. 6.7. Flowchar of Pyreg reactor process. Photo: www.pyreg.de

Biomacon Gmbh

The Biomacon reactor is also a slow pyrolysis auger reactor like the pyreg, but uses a more simple design for the secondary combustion of the pyrolysis gasses. The biomacon reactor was selected for use in the Oplandske Bioenergi facility in Norway, the facility at Sandnes kommune in Western Norway, and the pyrolysis reactor installed at Hjelmsäter farm in Sweden.

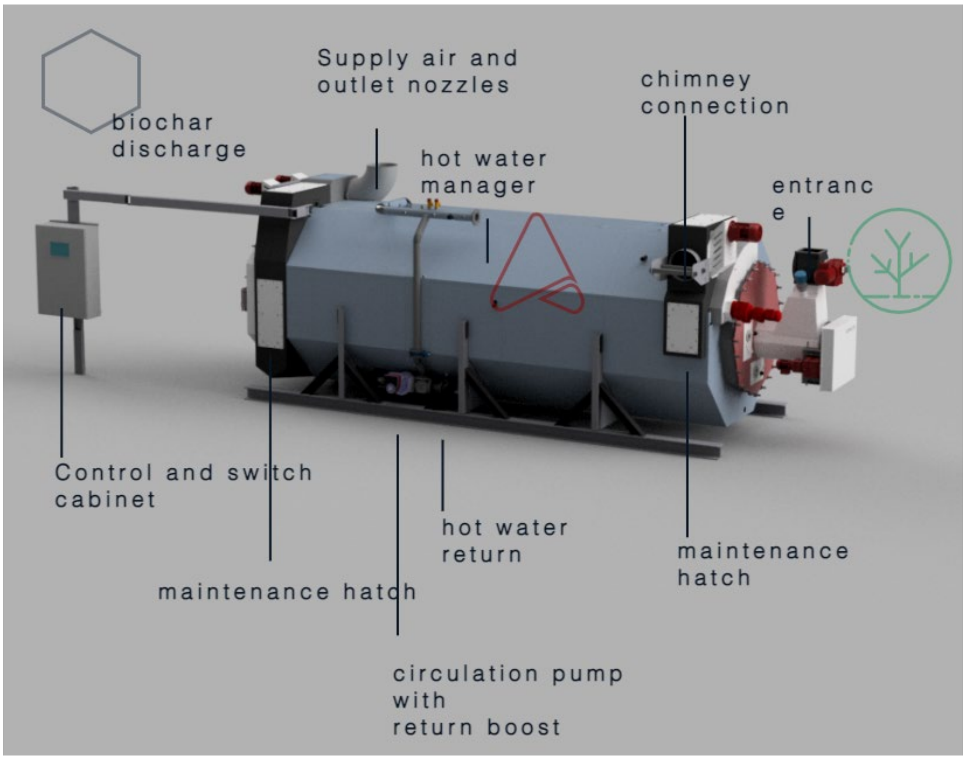

Fig. 6.8. Biomacon reactor schematic.

Carbofex Ltd. (Finland)

The Carbofex reactor is designed and manufactured in Finland. It is a slow pyrolysis auger reactor carbonizes up to 500 kg of wood chips per hour, turning it into 140 kg of biochar, and can optionally produce pyrolysis oil. The facility can produce 700 tons of biochar and 600 tons of oil per year. Their facility in Hiedanranta also supplies heat to the district heating network. The company and reactor is one of the longer established in Europe and their biochar is certified via the European Biochar Certificate (see: www.carbofex.fi).

Pyrocal Pty Ltd (Australia)

The Pyrocal reactor is an updraft gasifier where biomass enters the top of the reactor and is manoeuvred downwards in a series of chambers by rotating metal arms. The biomass dries and then is gasified, with biochar exiting the reactor at the bottom. The reactor has been commissioned in several international projects processing sugar cane bagasse, coffee shell, and most recently in a large scale biosolids project in Logan City, Australia. The reactor is autothermal meaning it does not require external energy inputs to operate the carbonization phase. Both stationery, transportable and mobile versions are available. (See: www.pyrocal.com.au)

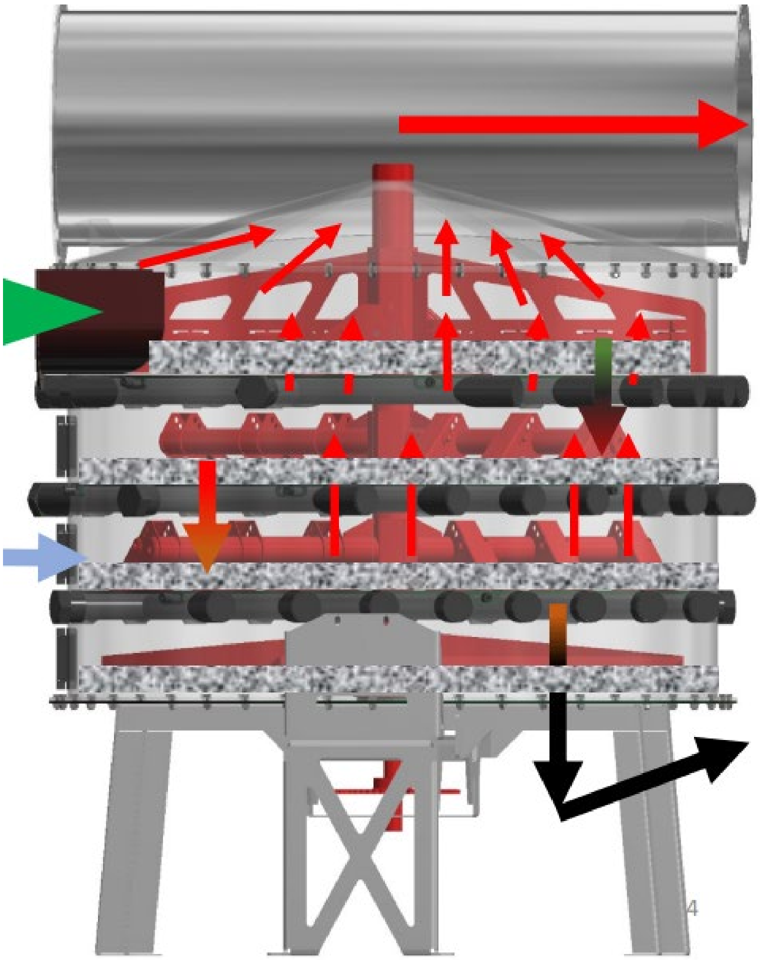

Fig. 6.9. Schematic of the pyrocal updraft gasifier. Photo: www.pyrocal.com.au

For each of the continuous reactors mentioned above there will be specific particle size and moisture requirements for the biomass feedstock. There exist many more reactors so what is described here is just a snapshot of what is available from around the world.

7 Effects on forest and seedling growth

7.1 Biochar as a forest growth enhancer

Biochar is widely used as a soil amendment in agriculture. It is known to increase soil pH, water and nutrient retention capacity, carbon and nutrient stocks (after pre-treatment) and the availability of nutrients (Biederman and Harpole 2013, Gundale et al. 2016, Page-Dumroese et al. 2017, Li et al. 2018). According to meta-analyses, biochar amendment increases agricultural plant productivity on average by 10–25%, and the greatest growth increments have been observed in acid, infertile and coarse textured soils (Biederman and Harpole 2013, Liu et al. 2013, Jeffery et al. 2017). Research from the Nordic countries generally shows a modest positive effect on agricultural soil quality (O'Toole et al. 2022).

So far, few studies have examined the possibilities of biochar to promote tree growth, especially in the boreal zone. A meta-analysis consisting of 17 studies indicates a potential for large tree growth responses after biochar additions, with a mean 41% increase in biomass (Thomas and Gale 2015). Most likely causes identified were increase of plant available P with biochar amendment and sorption of growth-inhibiting phenolics. However, far-reaching conclusions or generalizations cannot be drawn yet based on these studies because the majority of studies are short-term (< 1 year) pot experiments with small tree seedlings, and there are only few field trials. Furthermore, growth responses have been highly variable because they depend on climate, soil type, tree species, biochar characteristics and the amount of biochar (Thomas and Gale 2015, Page-Dumroese et al. 2017, Li et al. 2018, Sherman et al. 2018, Sarauer et al. 2019). Thus, more information is needed about the long-term effects of biochar on stand-level growth and yield, and there is a need for field experiments examining a range of biochars, soils and forest types in different climatic conditions (Page-Dumroese et al. 2017, Palviainen et al. 2020).

The first biochar field experiments in boreal forests support the perception that wood biochar promotes tree growth. The biochar amendment of 10 Mg ha^{-1} increased the diameter growth of dominant trees by 25% compared to control during three years in 20 years old Scots pine (*Pinus sylvestris*) forests in southern Finland (Palviainen et al. 2020). The positive growth responses were less pronounced in height (12% increment) than in diameter growth. The study site was nutrient poor (*Vaccinium*-type), xeric forest growing on sandy soil. Biochar likely increased tree growth because it improved soil water holding capacity and increased soil pH, microbial activity and nitrogen (N) mineralization rate (Palviainen et al. 2018, Zhao et al. 2019, Zhu et al. 2020). Similar results have been also found in a Swedish field experiment, in which the biochar amendment of 10 Mg ha^{-1} increased the biomass of Scots pine seedlings by 19% during 8-9 years (Grau-Andrés et al. 2021). These growth increments are the same order of magnitude as after N fertilization in boreal forests. Thus, biochar could provide an alternative to synthetic N fertilizers, and the use of biochar is potentially a more climate friendly option for increasing forest growth than synthetic fertilizers which production is energy intensive. Biochar can also improve the efficiency of N fertilization in tree production. The new "Biochar for carbon capture in forests (FORBIOCHAR)" research project lead by Norwegian research institute NIBIO will provide new information about the effect of N enriched biochar on tree growth. These study sites locate in two mature pine forests in SE Norway. The experimental setup contains four treatments: 1) Unfertilized control, 2) Biochar (2.5 Mg ha^{-1}), 3) N fertilization (150 kg N ha^{-1}), and 4) Biochar and N fertilization (2.5 Mg biochar ha^{-1} loaded with N, corresponding to 150 kg N ha^{-1}).

7.2 Biochar and seedling growth

Biochar addition has been shown to increase the growth of tree seedlings and enhance the colonization of seedlings by some ectomycorrhizal fungi (Robertson et al. 2012, Ortas, 2016, Grau-Andrés et al. 2021). This supports the idea that incorporation of biochar into nursery soil for seed germination and seedling growth prior to outplanting may be an appropriate method for introducing biochar into forests.

The use of biochar as an additive to or substitute for peat as a growth medium in tree nurseries has been starting to gain interest among scientists and producers, because peat extraction increases carbon emissions, impairs water quality and reduces biodiversity. The raw peat is limed and fertilized, and the production and use of these components has several negative environmental impacts, such as eutrophication, acidification, carbon emissions, and depletion of the ozone layer. Köster et al. (2021) studied the potential of biochar to improve the properties of the growth media and the growth of Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and silver birch (*Betula pendula*) seedlings. They added willow biochar (0%, 5%, 10%, and 20% of volume) to raw peat, and provided fertilization on three different levels (0%, 50%, and 100%) compared to common nursery practices. Biochar significantly increased carbon and nutrient (N, P, K) concentrations and had a liming effect on the growth media. Biochar amendment increased the aboveground growth of spruce seedlings and root biomass. Biochar also increased root biomass and root collar diameter of birch seedlings. Biochar amendment had a clear positive impact on the post-planting survival of all studied tree species (Köster et al. 2022). The best growth and survival of tested species were achieved if biochar amendment was combined with fertilization. Best survival and growth were attained with 20% biochar addition for Norway spruce and silver birch, while for pine the optimal amount of biochar was 10%. It can be concluded that biochar has potential in the nursery production of tree seedlings. The transition to biochar–peat mixtures in nurseries would decrease the need for peat extraction, liming and fertilization which could consequently decrease the detrimental environmental impacts of the nursery production of tree seedlings.

8 Soil carbon stores, climate change mitigation potential and emissions trading

8.1 Biochar and soil carbon stores

The addition of biochar to soil is a potential tool for carbon (C) sequestration and climate change mitigation because biochar C content is high, it is recalcitrant to decomposition, and the application rates to soil can be high, up to 10-60 t ha^{-1} (Woolf et al. 2010, Gurwick et al. 2013, Fuss et al. 2018). Biochar studies have mainly been conducted on agricultural soils, and very little information exists about the stability of biochar in the soil and the effects of biochar additions on C and nutrient cycling in boreal forests.

There has been a concern that biochar could increase decomposition rate of soil organic matter (priming effect) because biochar applications can improve soil properties for microbes (Zimmerman et al. 2011), and adsorb phenolic compounds, which inhibit organic matter decomposition in boreal forest soils (Zackrisson et al. 1996, Wardle et al. 2008). Studies from temperate and boreal forests have shown that soil CO2 effluxes remain unchanged or increase slightly only during the first months after biochar addition (Sackett et al. 2014, Bruckman et al. 2015, Gundale et al. 2015, Page-Dumroese et al. 2017, Palviainen et al. 2018, Zhao et al. 2019, Zhu et al. 2020). Short-term increases in soil CO2 effluxes are largely due to higher soil temperatures when black biochar is added to the soil surface (Bruckman et al. 2015, Palviainen et al. 2018). The meta-analysis by Maestrini et al. (2015) indicated that biochar can induce short-term positive priming effect but enhances long-term C sequestration by promoting physical protection of soil organic matter. Biochar may also slow down the rate of C mineralization because microbial extracellular enzymes are adsorbed to biochar (Jones et al. 2011, Zimmerman et al. 2011, Ameloot et al. 2013). Biochar addition has not been shown to change soil C turnover times or temperature sensitivity of organic matter decomposition in boreal forest soils (Zhao et al. 2019). In the long-term, biochar addition can increase soil C stocks by improving soil fertility and enhancing forest growth and litter production (Palviainen et al. 2020, Grau-Andrés et al. 2021). Thus, it seems that biochar is a promising tool to enhance the C sequestration in boreal forests. This could bring new income sources to forest owners if the greenhouse gas reduction potential of biochar is quantified (Sahoo et al. 2019).

8.2 Biochar and climate change mitigation potential

According to the IPCC climate change and land report, biochar is potentially an important climate change mitigation option with possibly large co-benefits for other ecosystem services at reasonable costs (low-hanging fruit). Enhancing soil C storage and the addition of biochar can be practiced with limited competition for land, provided no productivity/ yield loss and abundant unused biomass, that can be extracted without negative effects on site conditions. However, the impacts of large-scale application of biochar on the greenhouse gas balance of soils, or human health have not yet been explored.

Biochar addition can decrease soil greenhouse gas emissions (He et al. 2017). Several studies have reported decreased N_2O emissions after biochar amendment (He et al. 2017). The possible reasons are that: 1) the proportion of N_2O transformation to N_2 during denitrification is changed due to the elevated soil pH, 2) the activity of microorganisms involved in denitrification increases, 3) the adsorption ability of soil to ammonium and nitrate is improved, and 4) better soil aeration reduces denitrification rate (Cayuela et al. 2013, He et al. 2017). A review study by Li et al. (2018) indicated that biochar amendment in forest ecosystems generally decrease soil N_2O emissions and increase CH_4

uptake, whereas changes in CO_2 emissions are variable (negative, positive, or negligible). The changes in greenhouse gas emissions are biochar-, soil-, and tree species-specific (Li et al. 2018).

Biochar on the soil surface can alter albedo (reflection of solar radiation from the soil surface) due to its dark color which counteracts the climate mitigating potential of biochar (Kuppusamy et al. 2016, Smith 2016), as long as biochar remains on the soil surface. The albedo effect is likely short-lived in forests because the colonization by vegetation has been rapid after biochar amendment (Bruckman 2015, Palviainen et al. 2018).

Recent assessments estimate that the use of biochar could sequester between 0.6 Gt CO_2 yr^{-1} and 11.9 Gt CO_2 yr^{-1}, depending on the availability of biomass for biochar production (Fuss et al. 2018). Biochar has fewer disadvantages than a range of other negative emission technologies (NETs) because it can be applied to all managed land without changing its current use (Smith 2016), and potentially generating additional benefits in various contexts (Sohi et al. 2016). In contrast, many other NETs require land use change or compete for land for other uses. Many NETs require energy and/or they have large water footprint, whereas biochar can be used in energy production and biochar production does not require water (Smith 2016). Currently, high biochar prices prevent its large-scale application (Fuss et al. 2018), but see discussion of biochar-derived carbon credits below.

8.3 Carbon credits from biochar production and use

8.3.1 Carbon credit trading

The concept of carbon credits and carbon credit markets are results of *The International Emissions Trading mechanism* under the Kyoto protocol (KP). This mechanism allows countries with excess of permitted emission units to engage in carbon trading and selling such units to other countries. This created a carbon market that spurred the development of *The Greenhouse Gas Protocol* (World Business Council for Sustainable Development and World Resources Institute 2005) being a primary document for carbon accounting. In this document key research institutions, corporate partners, environmental groups, and energy industry partners “identified an action agenda to address climate change that included the need for standardized measurement of GHG emissions”. The document defined a standard measurement unit of GHG emissions to be one ton of CO2 or the equivalent amount of a different greenhouse gas (tCO_2-e). Furthermore, in a trading context, they referred to this unit of 1 tCO_2-e as one **carbon credit**.

The fundamental motivation for introducing carbon credits and carbon trading is economic efficiency in reducing greenhouse gas emissions. The Kyoto Protocol mandated industrialized nations to cut their greenhouse gas emissions significantly. Later, the Paris Climate Agreement of 2015, which replaced the Kyoto Protocol, included commitments from all major GHG-emitting countries to reduce their emissions. The Paris agreement introduced new quantitative targets and timelines for national GHG reductions. These reduction targets represent a major driver for the development of the carbon market, especially the compliance carbon market sector (see below). Another driver is the commitment or intention of companies, organizations and individuals to improve their carbon footprint, essentially facilitating the voluntary carbon market sector (see further below).

Compliance carbon credit markets

These markets are also known as Emissions Trading Systems (ETS). Compliance carbon credit prices are largely driven by government policies to fulfil national GHG reduction commitments under the

Kyoto Protocol and Paris agreement. The government policies dictate maximum emission limits (also known as allowances or credits) typically declining over time. In the EU compliance market, for example, there are more than 10 000 power plants, aviation companies and manufacturing entities with a commitment to reduce GHG emissions to at least 55% below 1990 GHG levels by 2030 and achieve net-zero GHG emissions by 2050 (Carbon credits 2023). The traders on these markets are carbon emitters that buy or sell carbon credits based on emissions compared to their allowance limits. Due to the upper (maximum) emission limits and possibility to trade, these markets are also labelled «cap and trade» markets.

Currently, there are three major Emissions Trading Systems around the world: 1) The European Union's Emissions Trading System (EU), 2) The California Global Warming Solutions Act (USA), and 3) The Chinese National Emission Trading System (China). The following description is a summary derived from Carbon credits (2023):

The EU ETS covers the 27 EU states plus Iceland, Liechtenstein, and Norway. The total GHG emissions in this jurisdiction amount to 3.9 billion tonnes per year, making it the second largest ETS in the world. The EU ETS has been operating since 2005 and has collected USD $80.7 billion since start, with USD $21.8 billion in 2020 alone. Carbon credits are currently priced at USD ~$80 per ton on the EU ETS.

The California ETS has been operating since 2012 and its jurisdiction covers California only. The overall GHG emissions in this jurisdiction amount is 425 million tonnes per year. It has collected USD $14.24 billion since inception, (including USD $1.7 billion in 2020). The current price for carbon under the California ETS is USD ~$30 per ton.

The Chinese National ETS began its operation in 2021 based on pilots in eight major regions between 2013 and 2016. The overall GHG emissions in this jurisdiction amount to 12.3 billion tonnes per year. The current price for carbon on the China ETS is USD ~$9 per ton.

Other compliance credit markets (ETS) that exist today are the Korean ETS, the Kazakhstan ETS, the New Zealand ETS, the Japan ETS, the Canada ETS, and the Mexico ETS.

Voluntary carbon credit markets

These markets are collectively labelled «voluntary» because trading here is voluntary and they are open to any enterprise, organization or individual person. Furthermore, these markets are not regulated by governmental administration (although governmental quality control has been carried out, see Cames et al. 2016).

The voluntary carbon market is tightly linked to **carbon offset projects**, that is projects removing greenhouse gases from the atmosphere or preventing emissions that would occur if the project did not exist. These projects exist outside the compliance credit markets and they are called «offsets» for their ability to counteract industrial carbon emissions. Such offset projects are quantified, verified and translated into carbon credits to be traded as representations of avoided greenhouse gas emissions (Donfrio et al. 2021, for a critical view see Gifford 2020). This voluntary carbon market is mainly driven by companies and corporations that work to lower their overall compliance costs and/or make climate pledges (claiming their activity is carbon neutral or even carbon negative).

Carbon offset projects have existed for more than 20 years. Traded volumes of credits from such projects had an early peak during 2008-2010 sinking to a bottom level in 2017, and subsequently rising to an unprecedented peak in 2021 (fig. 8.1). Today, nearly 90 % of the voluntary carbon credits are linked to forest/land use or renewable energy projects (Donfrio et al. 2021).

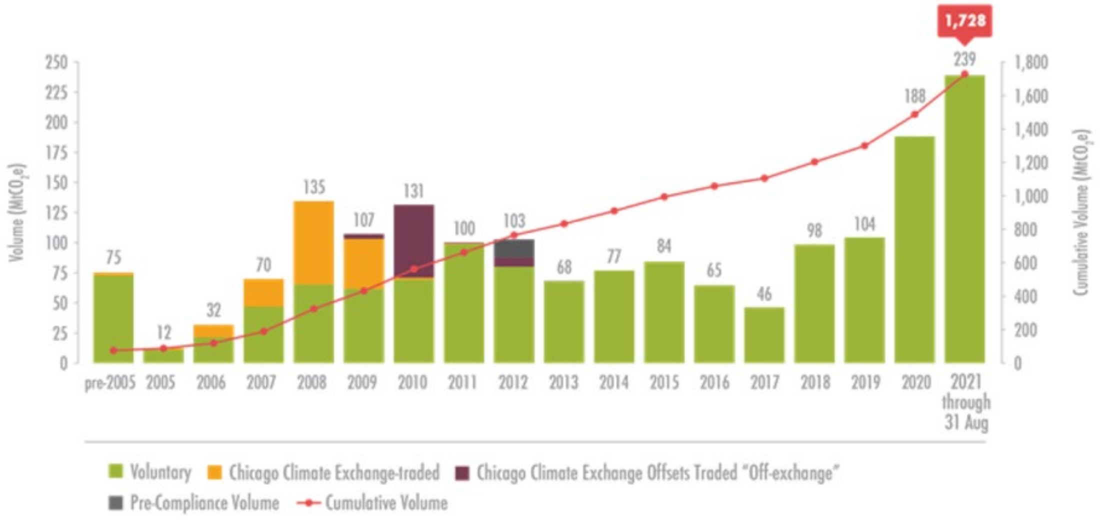

Figure 8.1. Market size by traded volumes of voluntary carbon offsets, pre-2005 to August 2021 (from Donfrio et al. 2021).

The early carbon offset projects were characterised by much uncertainty when it came to practical implementation, quality control and verification of their actual performance in greenhouse gas sequestration. Questionable, malfunctioning, and obviously dishonest carbon accounting occurred frequently. Thus, the derived carbon credits soon got a poor reputation as greenwashing with exaggerated environmental impact. A 2016 study by the European Commission found that 85% of the offset projects used by the EU under the UN's Clean Development Mechanism, one of the largest carbon offset markets, failed to reduce emissions at all (Cames et al. 2016). Subsequently, the standards improved and became more streamlined (van der Gaast et al. 2018, see recent review of forest carbon offset projects by Pan et al. 2022). There are, however, still some fundamental challenges associated with the voluntary carbon credit market, including:

- Different ways to measure and quantify climate impact of offset project (see discussion of carbon credit quality and prize differentiation under 8.3.3)
- Large complexity and lack of governmental regulations of this market (although this is under development, see European Commission 2022)
- A large surplus of old carbon credits available for purchase to very low prices (Turner et al. 2021).

8.3.2 Biochar-derived carbon credits

Biochar has been acknowledged for decades as a carbon-rich material that is very recalcitrant to biological degradation (chapters 5.2 and 8.1). Thus, eager proponents started early to argue that biochar use for soil amendment should qualify as carbon offset projects. Back in 2011 Ernsting and colleagues wrote «Biochar has not yet been included in any carbon trading mechanisms and soil carbon sequestration is excluded from both the Clean Development Mechanism (CDM) and the EU Emissions Trading Scheme, which together account for approximately 97% of carbon trading worldwide» (Ernsting et al. 2011). At that time the carbon offset projects were under increasing scrutiny as evidence indicated they did not deliver real GHG savings and were vulnerable to malpractices, including illegal manipulation and speculation (see Cames et al. 2016). The EU has decided to continue excluding soil carbon sequestration from the EU Emissions Trading Scheme until at least 2020 and does not support soil carbon inclusion into the CDM. Biochar proponents then shifted focus to the voluntary carbon markets.

Although international agreements focused on GHG *emission reductions*, there was a growing understanding that negative emission technologies are important to reach the Paris agreement of limiting climate change to well below 2 °C. In this context the conversion of biomass to biochar and subsequent application to soils was identified among seven relevant negative emission technologies and it was considered among the most promising technologies (Minx et al. 2018, EASAC 2018).

An important milestone for developing biochar-derived carbon credits was an IPCC report on methodological considerations for estimating the change in soil organic carbon stocks from biochar amendments (IPCC 2019). This report synthesized existing data and provided numbers for remaining fractions of soil organic C stocks from biochar amendments over a 100-year time frame, specifically 0.80 for biochar from medium pyrolysis temperature (450-600 °C) and 0.89 for biochar from high pyrolysis temperature (> 600 °C). Subsequently, it has become evident that 75% of biochar from high pyrolysis temperature consists of stable polycyclic aromatic carbon and will persist after soil application for more than 1000 years independent of the soil type and climate (Schmidt et al. 2022).

This recent knowledge synthesis has facilitated operational carbon credit methodologies for biochar utilization in soil and other applications (concrete, asphalt). Currently (February 2023) these methodologies include the European Biochar Certificate, PuroEarth, the Verra methodology, and the Climate Action Reserve (Etter et al. 2021, see also https://www.european-biochar.org/en).

8.3.3 Price and quality of carbon credits

The above section on Compliance carbon credit markets showed quite large price differences per carbon credit from US$ 9 in the Chinese ETS to US$ 80 in the European ETS. The price variation is even larger in the voluntary carbon market, from US$ 3 to US$ 100+ (Smith 2021). These differences reflect several, partly correlating factors: age of origin (old credits are cheaper, generally also of lower quality), market type (the voluntary market prices are on average lower than the ETS market prices) and carbon credit quality (where increasing quality implies increasing certainty for durable or permanent, net removal of greenhouse gases from the atmosphere). Furthermore, the differences between the different ETS markets reflect costs of additional emission reductions for companies in the respective markets.

Volume

The volume of carbon credits being traded in the voluntary market has increased sharply since 2017 (fig. 8.1) and is expected to increase at an accelerating rate in the coming years (Shell and BCG 2022). This is partly driven by obligation of increasing emission reductions for companies in the ETS markets. Furthermore, nations and large companies (both within and outside the compliance markets) are pledging ambitions of becoming net zero emitters of greenhouse gases. Last year, 702 out of the 2000 largest companies worldwide had committed themselves to net zero targets (Zerotracker 2022). This is enforced by observers that scrutinize corporate and national pledges for details that can show whether the pledges are serious about delivering their net zero target (Black et al. 2021, Zerotracker 2022).

Another trend in the carbon marked is that purchase of credits (retirements) seems to accelerate faster than development of new validated offset projects (issuances of credits), indicating a tightening of supply/demand (Shell and BCG 2022).

Quality

Since global carbon markets developed some 20 years ago, the quality of carbon credits has been defined by technical aspects like accounting methodology, additionality, durability, transparency, independent verification, etc. This has made the carbon markets complicated and it is difficult to compare alternative credits claiming similar carbon offsets. The last 2-3 years the focus has shifted from such technical aspects (still being important) to type of carbon offset projects - whether they are emission reduction projects or greenhouse gas removal projects. In a market analysis Shell and BCG (2022) stated that "Over the course of the 2020s, buyer preference is likely to shift towards removal credits, driven by concerns around quality and pressure from external stakeholders. If technology-based removals, such as direct air capture (DAC) and bioenergy and carbon capture and storage (BECCS), show the expected cost reductions … this … will help them gain market share." It can be added that most of the biochar applied to soils appears to have a persistency of more than 1000 years and hence can be considered as removals of equal permanence as DAC and BECCS (Schmidt et al. 2022).

In the next years, we can expect stricter quality differentiation of carbon offset projects as the EU is proposing a Union certification framework for carbon removals to be developed by the end of 2025 (European Commission 2022). This framework operates with three removal categories: a) "permanent carbon storage" storing atmospheric or biogenic carbon for several centuries, b) "carbon farming" meaning land management that results in the increased carbon storage in living biomass, dead organic matter and soils and c) "carbon storage in products" meaning storage of carbon in long-lasting products or materials.

Price and price differentiation

Above, we stated that there is a price variation in the voluntary carbon market from US$ 3 to US$ 100+ per carbon credit (Smith 2021). An important trend is that this price differentiation in the market is increasing. This is partly an effect of geographical variation (especially the European ETS prices have increased more rapidly than elsewhere) and partly an effect of removal credits increasing more than emission reduction credits (World Bank 2022).

The bottom price level at US$ 3 comprises 10-15 years old carbon credits of dubious quality that exist in surplus and appear unsellable due to a greenwashing reputation. At the other end of the price range, we find carbon credits sold for 100-200 US$ and biochar-derived credits belong at this price level (see below).

This price differentiation between credit types appears to reflect buyers' increasing desire to comply with net zero strategies, i.e. buyers view that emission reduction credits do not offset their own emissions and instead they want removal credits. Removal technologies also avoid challenges regarding additionality, permanence and baseline accuracy of forest- and land-use credits.

Biochar carbon credit prices

Biochar-derived carbon credits have existed for about 4 years, but it is evident that these carbon credits already have obtained high credibility for quality as judged by their market prices. In the US, biochar-derived credits had a market price around 100 US$ 1-2 years ago (Thengane et al. 2021, Elias et al. 2022). In a recent update of January 2023, the marketplace Puro Earth listed 23 biochar projects with prices ranging from US$ 98 (100 EUR) to US$ 524 (535 EUR) per ton of CO_2 removal (see https://www.givinggreen.earth/carbon-offsets-research/biochar-%26-bio-oil).

A Norwegian company with industrial biochar production from wood chips (Obio, https://www.obio.no/home) can serve as an illustrating example of some market details. Their carbon credits are derived from the European Biochar Certificate (EBC). The Obio carbon credits has a market price that increased rapidly since they started commercial production in 2021. When we (the SNS network behind this report) visited the Obio production plant late spring 2022, the market price per carbon credit was 140 US$ and it has subsequently increased to 192 US$ by February 2023 (E. Stuve, personal communication). Their market analysis predicts conservatively that this price will not decline in 2023.

When Obio sell their biochar, they offer their customers to buy the biochar including the carbon credit. But Obio also offers a discount on the purchase reflecting the carbon credit price if the customer wants to buy the biochar at a lower price. In this latter case, Obio instead sell the carbon credit on the carbon credit market. To fulfil the EBC verification procedure, Obio has a detailed accounting system where every single bag of produced biochar has a serial number, and they keep track of whether it was sold with or without the carbon credit.

9 Effects on biodiversity

To date, there are very few field-based studies that have been carried out in forests in the Nordic region. Even fewer such studies have described some aspect of biodiversity. Biodiversity shifts in response to biochar can be characterized in different ways, including species richness, evenness, diversity indices, or composition and resilience. Thus far, studies describing these types of biodiversity measures in response to biochar treatments have mainly focused on soil or plant communities.

9.1 Soil communities

One of the first studies on biochar in the Nordic region, by Pietikainen et al. (2000), created four types of biochars (referred to as charcoal in the manuscript), and evaluated their effects on soil microbial community development, using phospholipid fatty acid (PLFA) analysis. The work showed that PLFA profiles significantly differed between biochars, indicating that biochar properties can have a significant influence on the composition of microbes that colonize them. While Pietikainen was a laboratory incubiation study, several recent studies have also looked at microbial community response to biochar in the field, with variable results. Gundale et al. (2016) utilized a field experiment where 10 tons ha^{-1} of biochar were added to soils, either on the surface, or mixed into the soil, with parallel mixed and unmixed biochar control. This study showed that biochar addition to the soil reduced fungal and bacterial biomass in the soil, as well as decreased the ratio of fungi: bacteria. Several recent Finnish studies have also evaluated the response of microbial communities to biochar. Qu et al. (2022) added four types of biochar to a boreal Scots pine forest, where wood decomposition was measured. The four biochars were made by crossing two pyrolysis temperatures (500 or 650 C) with two addition rates (0.5 kg m^{-2} and 1.0 kg m^{-2}). The biochar treatments changed the wood-inhabiting bacterial community structure during the decomposition period. The pyrolysis temperature and the amount of applied biochar had no effect on the bacterial community structure but shifted the abundance of certain bacterial taxa. Likewise, another Finnish study, by Ge et al. (2022) evaluated changes in soil bacterial communities in the same study system. The authors reported that application of biochar produced at 500 °C had a lower abundance of *Actinobacteria* and *Verrucomicrobia*, while bicohar produced at 650 °C had a higher abundance of *Conexibacter* and *Phenylobacterium*. They further reported that when biochar produced at 650 °C was applied, applying 0.5 kg m^{-2} had a higher abundance of *Cyanobacteria*, *Conexibacter*, and *Phenylobacterium* than that of 1.0 kg m^{-2} ($P < 0.05$).

9.2 Plant communities

While relatively few studies have reported soil community responses to biochar addition, we are aware of only one study that has reported vegetation composition and diversity responses to biochar addition. In the field study by Gundale et al. (2016), four years after the study began, biochar application was found to reduce plant species richness, regardless of whether it was applied to the surface or mixed into the soil. Further, biochar mixed into the soil significantly reduced total plant cover relative to control or soil mixing only treated plots. In a follow up study to Gundale et al. (2016), 9 years after the experiment began, Grau-Andres et al (2021) showed that biochar still had some lingering effects on vegetation composition, however, these effects were much weaker than the effect of mixing. Specifically, biochar promoted abundance of the dominant tree (i.e., naturally regenerating *P. sylvestris*) and shrub (i.e., *Calluna vulgaris*), and impaired graminoids (e.g., *Deschampsia flexuosa*, *Calamagrostis lapponica*) and forbs (e.g., *Trientalis europaea*, *Melampyrum pratense*). In the same study, Grau-Andres et al. (2021) also showed that biochar enhanced tree growth by ca. 16%.

10 Research questions for biochar in forestry

As mentioned above, the use of biochar in a forestry context is still relatively new despite a few scientific experiments, that greatly contribute to the understanding of biochar as a soil amendment in a forestry context. Other than in agricultural systems, commercial examples of using biochar in forestry are rare. The reason may be found in negative results in cost/benefit analyses, lack of knowledge among the forest industry, missing examples that clearly demonstrate benefits in a specific context and still unresolved scientific questions. The following focuses on needed research to help develop research trajectories to answer questions and facilitate the application of biochar as soil amendment in different forestry contexts.

10.1 Incorporation of biochar in the soil horizon

In order to unfold its desired function(s) in the soil, biochar needs to be embedded in the soil matrix and thus incorporated in the soil horizon. In agriculture application, ploughing may be a common practice to ensure rapid incorporation of biochar in the topsoil horizon. Despite from cases of punctual application (e.g. in planting holes during manual re-planting of a tree stand) or soil preparation similar to agricultural practices (e.g. in case of short rotation crops), large-scale incorporation of biochar into the topsoil horizon is difficult in forest stands. In the regeneration phase some mixing between biochar and soil could take place during ordinary site preparation (e.g. disc trenching or mounding), though this has not been tested in practice. In growing forests, biochar can only be applied on the soil surface. To incorporate bichar in the active soil horizons by spreading it on the surface and letting it incorporate by bioturbation and translocation within soil pores can take years to decades. It was demonstrated, however, that ground biochar (up to 5 mm grain size) was incorporated into the organic layer within a couple of months (Bruckman, 2015). Questions remain in which form biochar should be spread on the surface and besides concerns of erosion of light particles (e.g. by wind), economic considerations do play an important role and are often decisive if a certain procedure can be implemented. Existing technology, applied in a different context may be part of the solution, e.g. by pelletizing biochar and distribution of these by means of standard equipment (Page-Dumroese et al. 2017). It is vital to understand the nexus between minimizing disturbances in the topsoil horizons, and the most efficient means of biochar distribution on larger scales to generate the desired functions (carbon storage, improved cation exchange capacity, liming effect etc.). Conclusions may be drawn from established practices, such as liming and/or ashing.

10.2 Development of systems scenarios

To raise awareness among various stakeholders, from forest owners to policy makers, science need to to develop systems-based scenarios of biochar use in forestry, with the aim to demonstrate the vast potentials of biochar use in a forestry context. This needs thinking across systems boundaries, and may lead to a regional concept that can include energy generation, extraction and/or immobilization of pollutants and agriculture. Sohi and Kuppens (2016) present a number of potential circular and directional appraches, that can be used to guide studies with a focus on real application scenarios. It may include the development of a valuable product, such as a soil mixture containing biochar for gardening, while some of the biochar is also used in a forestry context and biomass may be sourced from a specified region, where available biomass comes from forestry and agriculture, in varying amounts troughout the year. While science should be tasked to develop such scenarios, it would be important to establish demonstration plants at the scale of implementation (Amonette et al. 2021), that are embedded in a regional concept, including the entire supply chain (Bruckman et al. 2016).

10.3 Impact on forest growth and carbon stocks

Long-term effects of biochar on forest growth should be studied by continuing the monitoring of the existing field experiments. Weathering, leaching and microbial degradation of biochar may alter biochar physical and chemical properties (Mia et al. 2017), and influence tree growth responses with time (Thomas and Gale 2015). The recalcitrance of biochar to microbial degradation and long residence time in the soil implies that biochars can potentially have long-persistent positive effect on forest growth. The long-term positive impact of biochar on plant growth has been shown in anthrophogenic char rich Terra Preta soils (Glaser and Birk 2012). Tree growth responses to biochar addition can be highly variable and specific to particular environments and tree species. Thus, further research is needed to understand how tree growth depends on properties, amount and placement method of biochar as well as tree species, stand age, site characteristics, climate and weather conditions.

A particular question of concern remains in regard to carbon sequestration potentials of biochar in forest ecosystems. While research in agriculture has led to a confident level of understanding of biochar stability in soils, including associated soil fertility and elevated net primary productivity (NPP), results in forest environments are still needed to provide comprehensive answers in different contexts. Results published so far indicate that biochar can indeed contribute to carbon sequestration in boreal forests (e.g. Palviainen et al. 2018), but it needs more research to confirm these results in a multitude of settings. Li et al. (2018) present a comprehensive synthesis, that list the influence of biochar amendment on soil (autotrophic and heterotrophic) respiration still unresolved despite solid understanding of respiration and their components in forest soils. Potential loss of carbon due to changing wildfire regimes may be another reason for considering biochar production. Excess biomass accumulation is an issue in view of increased wildfire risks. Therefore, concepts of mobile pyrolysis units, that are suggested in North America (McElligott et al. 2011) may be re-assessed and considered in boreal forests to reduce the risk of carbon losses in the system.

10.4 Impact on biodiversity

The physio-chemical characteristics of biochar alter soil properties and thus influence the habitat quality for soil fauna and flora. At the same time, the scientific community is alerted due to significant loss of biodiversity, a basis for human existence. An area of great concern should therefore be the consequences of biochar amendment in forests on biodiversity. Scientific evidence in this domain is still limited, but they do exist, e.g. in case of stand establishment by using seeds (Drake et al. 2015). The authors show that biochar amendment not only increased total carbon stocks, but also biodiversity. However, applying biochar in an intact forest ecosystem may rapidly change soil chemistry (liming effect), which can be detrimantal to certain species. Potential pollution (heavy metals or polycyclic aromatic hydrocarbons) triggered by biochar amendment is currently not well understood and needs more research to avoid any negative effects on soil fauna (Hilber et al. 2017).

While several Finnish studies have characterized bacterial species level responses to biochar, additional studies are needed to describe fungal composition and diversity, as well as other components of the soil food web. Further, many more studies are needed to address the impacts of biochar on plant community composition and diversity, as well as other components of aboveground diversity (e.g. lichens, insects, and vertebrates). Future work on biochar impact on diversity should not only describe components of diversity, but also describe the functional significance of diversity, such has been done well so far for studies on soil biota (e.g. Gundale et al. 2016, Ge et al. 2022, Qu et al. 2022).

10.5 System boundaries and tradeoffs

Biochar amendment in forest contexts may come with certain tradeoffs, starting from biomass availability (demand-side competition for biomass where one needs to distingiuish between technical and sustainable potentials to avoid negative environmental impacts on forest sites), economical indicators (costs of production and amendment - currently, there is a greater demand for biochar as compared to supply in Europe), and impact on essential environmental services (supply of clean water of many forest ecosystems, potential contamination issues etc., as described above). Therefore, systems approaches are needed to understand these tradeoffs better. Scenarios developed should be based on results from continuous monitoring of existing experimental sites in forests, and more research plots should be established. A successful implementation of biochar in forest operations needs to address the entire supply chain and is therefore depending on results derived from demonstration facilities.

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Appendix

Overview of biochar experiments in forestry in the Nordic-Baltic countries

Country	Location name, start year	Lat, long	Species, forest age/stage	Treatments/biochar amount, ton ha^{-1}	Purpose of experiment	Results published in/ contact:	Result summary
Estonia	Maardu cut-away peatland, North Estonia, 2022	59° 41'N 25° 05'E	*Betula pendula*. Planted 1-year-old seedlings	Biochar (produced by Carbofex, Finland) mixed with wood ash, 5 t/ha, 10 t/ha, control	To determine the short-term response of Silver birch to addition of biochar + wood ash, and study changes in the chemical composition of the growth substrate and ground layer vegetation	N/A. Contact person: Katri Ots, Estonian University of Life Sciences	Results show changes in seedling growth and vegetation species composition because of changes in the structure and chemical composition of growth substrate.
Finland	Juupajoki, Hyytiälä Forestry Field Station, southern Finland, 2015	61° 48'N 24° 18'E	*Pinus sylvestris*. 20 yrs old, naturally regenerated	Wood biochar (pyrolysis temperature 500°C and 650°C), 5 t/ha , 10 t/ha and control	Assess the effects of biochar on soil properties, C dynamics (soil respiration), N mineralization, microbial community, microbial biomass and tree growth.	Palviainen et al. 2018. Plant Soil 425:71–85, Zhao et al. 2018. Soil Sci Soc Am J 83:126–136, Palviainen et al. 2020. For Ecol Man 474: 118362, Zhu et al. 2020 Ann For Sci 77: 59.	Short-term increase in soil respiration because biochar increased soil temperature. N mineralization on average higher in the organic layer of biochar plots. Soil pH increased, no change in microbial biomass. Biochar increased tree growth (25% greater diameter growth in 10t/ha biochar treatment compared to control).
Latvia	Madona region, Jaunkalsnava municipality, Forest Res station, 2022		*Salix alba*. 1 year old, planted by 20 cm cuttings	Biochar comercial product of Marienburg company.	Improvement of soil physical properties (low density), organic matter and increase water keeping capacity.	N/A. Contact person: Dagnija Lazdina, Latvian State Forest Research Institute "Silava"	N/A
Norway	Nesteby, Kongsvinger, SE Norway, 2020	60°12'N 12°06'E	*P. sylvestris*. Older production forest + regeneration, plus lab	Biochar, biochar loaded with N, control. Ca. 2.5 t biochar/ha, 150 kg N/ha	Assess effects of (N-enriched) biochar as forest fertilizer. Growth response and C sequestration, soil C dynamics, persistence of biochar in soil, N use efficiency, environmental impacts.	N/A. Contact persons: Jogeir Stokland/Kjersti Holt Hanssen, Norwegian Institute of Bioeconomy Research	N/A
Norway	Kjernmo, Nes, SE Norway, 2020	60°01'N 11°27'E	*P. sylvestris*. Older production forest, plus lab	As above	As above	As above	N/A
Sweden	Åheden, Svartberget, N Sweden, 2011	64°14'N 19°46'E	*P. sylvestris*. Establishment phase	Biochar, soil mixing, biochar addition followed by soil mixing, control. 10 t biochar/ha.	Assess the effects of adding biochar with or without soil mixing on soil chemistry, respiration, microbial community and vegetation	Gundale et al. 2016. The effect of biochar management on soil and plant community properties in a boreal forest. Glob Change Biol Bioen 8: 777-789.	Biochar enhanced soil N mineralization and NH4+ concentrations regardless of soil mixing treatment but had no impact on the availability of NO3- , most soil microbial community parameters, or soil respiration. Almost no effect on vegetation.

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