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Implementing circular economy principles in the use of horticultural peat products produced in Estonia and reducing related greenhouse gas emissions in the LULUCF sector

Implementing circular economy principles in the use of horticultural peat products produced in Estonia and reducing related greenhouse gas emissions in the LULUCF sector

Final report

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Introduction

The European Union has set a target of achieving climate neutrality by 2050 – a goal that needs a contribution from all sectors. Pursuant to Regulation (EU) 2018/841 of the European Parliament and of the Council (hereinafter referred to as the LULUCF Regulation), the land use and forestry sector, which also includes managed wetlands and peat production, will be included in the European Union's energy and climate policy framework, and instead of reporting data on the greenhouse gas (GHG) emissions from this sector, a stricter accounting system related to the national GHG reduction obligation will be implemented. Similar to other land use categories in the LULUCF sector, the accounting will also be period-based for wetlands. The LULUCF emission reduction/sequestration target is divided into two periods, the periods 2021-2025 and 2026-2030, respectively. Due to the lack of data and high uncertainty, the managed wetlands category will not be considered separately in the second reporting period, but the emissions target will be common to the entire LULUCF category. Each Member State has a target for reducing emissions/increasing sequestration by 2030, set in relation to the average value for the period 2016-2028. Compliance checks on GHG sequestration and emissions from managed wetlands for the period 2026-2030 will be carried out in the 2032 national inventory report.

The European Union Climate Regulation increased the EU-wide GHG reduction ambition and set a climate target of reducing net GHG emissions by -55% by 2030 compared to 1990 levels. In this regard, the LULUCF Regulation and national GHG emission obligations for the land use sector were also amended, according to which a no-debit rule applies to the Estonian LULUCF sector in the period 2021-2025 and the 2030 target is to reduce emissions by 0.434 million t CO2eq compared to the average or baseline level for the period 2016-2018. Unless extensive changes are made, Estonia is unlikely to meet the carbon sequestration target. Historically, Estonia's LULUCF sector has been a net sink, primarily due to carbon sequestration from forest management, which offsets emissions from other land use sectors. According to the 2024 National Inventory Report (NIR), the Estonian land use sector became a net emitter of carbon for the first time in the 30-year reporting period since 2014, as the carbon stock of forests has decreased. According to the analysis of the sequestration capacity of the LULUCF sector commissioned by the Ministry of the Environment in 2021, it is possible to increase the sequestration of the LULUCF sector by approximately 0.5 million t CO_2eq by 2030, although the analysis of horticultural peat was very superficial and one-sided. The analysis mentioned the idea that to achieve climate goals, it is not enough to only support measures to increase sequestration, but also to actively contribute to research and activities that promote emission reduction; in the case of peat, the need for additional research and improvement of methodologies in horticultural peat and peat production areas has been highlighted.

Reducing carbon emissions in the LULUCF sector is extremely important for Estonia from an economic point of view, including for the peat industry itself. If more precise data is not available, countries can use the simplified IPCC's Tier I methodology as the basis for calculating emissions. The aim of this project is to find out whether and to what extent emissions from the peat sector have been overestimated according to the current simplified calculation methodology and what a more precise calculation methodology could be that fits into the framework of the national greenhouse gas inventory. Reducing emissions from horticultural peat through the introduction of circular economy and sustainable carbon cycle principles and new practices, as well as through even more sustainable use of peat and the implementation of the carbon cycle of the extended peat value chain, will contribute to the balance of the LULUCF sector's carbon budget, and together with forest management, will help to achieve net removals of the sector again. In the light of the EU objectives of Fit for 55, this is a critically important issue for Estonia.

Based on relevant international studies, forecasts and trends in peat market demand in recent years, it is known that the need for horticultural peat will not decrease. This is especially important to consider in the current geopolitical situation, where access to various raw materials has been disrupted for a long time and significant problems are arising in the global food supply. At the same time, most of the industrially produced vegetables for aquaculture are grown in peat-based growing media. Therefore, it is important to find ways to reduce greenhouse gas emissions associated with the use of peat in order to ensure the possibility of continuing to use it. In the production and use of horticultural peat, attention has so far been mainly paid to the properties and safety of the ingredients used, both from the point of view of plant diseases and food safety, but little attention has been paid to the after-use use of the substrate. So far, there has been enough resource on the market and its availability has not been an issue (there has been no shortage or competition for the resource as such), which is why there has been little attention to after-use in the absence of an urgent need. According to current practice, the already used growing media is mainly composted, used in landscaping or as a soil improver – in cases where the specific properties of the material are no longer of primary importance. This creates good conditions for the development of better circular economy measures based on climate goals. However, for this it is important to know what the post-use physical and chemical properties of the substrates are, how recycled or reusable horticultural peat reacts and how it is possible to direct their post-use properties in the production and use of growing substrates in such a way that raw materials that can be recycled are created.

Although the peat industry has historically been an important economic sector in Estonia, not to mention the current period, little is known about the after-use practices of growing media. In order to implement circular economy measures, it is necessary to describe the main areas of use of horticultural peat, the quality demands for the substrates, the material flows and the after-use or waste management practices. The composition of the substrate depends on the area of use, because the substrate must meet the purpose of its use, which is very different due to the different growing periods and demands for water, pH and nutrients of different plants. For example, after pre-growing small plants the substrate moves with the plant to the next stage, either to a greenhouse, a pot or open ground. In the latter case, it is not possible to recall the substrate used for such purposes from the market, because the substrate remains in the soil as a soil improver, which is why the carbon contained in the peat substrate is not released into the atmosphere in its entirety, but remains partially bound to the soil. At the same time, in greenhouses, the growing media is changed regularly to prevent the spread of plant diseases. Some of it is composted, some is used in landscaping, some as a soil improver, etc. The different proportions of use are not known at the moment.

This study is the first stage that provides input for specifying the indirect or off-site emissions related to the production and use of Estonian horticultural peat and thereby creates the prerequisites for reducing emissions through better management, but if the results are positive, it could provide bases for launching broad research covering European countries and regions to investigate the possibilities of reducing the climate impact of the horticultural sector and related food production in a broader sense, its economic profitability, and the development of the necessary legal framework.

Formation and properties of peat

One of the main characteristics of mire ecosystems is the sedimentation of plant remains as a peat, because the high water level in the mire prevents the oxygen needed for the decomposition of plant remains from reaching them. The development history of each bog is somewhat different from the others – depending on the climate, water regime and chemistry, different plants have grown there over time – this is also reflected in the structure of the peat deposits. Generally, the nutrient content in the mire decreases during its development from a fen to bog – the thickening peat layer increasingly isolates the vegetation from the nutrient-rich groundwater, which is why only plant species with low nutrient demand can survive in the bog. Therefore, reeds, brown mosses, deciduous trees and sedges that grow in more nutrient-rich conditions and decompose more easily are replaced by peat mosses, pines and cottongrasses. According to the specific characteristics of the plant species and their nutritional content, a distinction can be made between well-decomposed fen peat and poorly decomposed bog peat. The fen peat is more decomposed, with higher pH and nutrient content than bog peat.

Peat does not form or decompose spontaneously; both processes are initiated by microbial organisms that break down long, complex carbon compounds into simpler ones. When peat is formed, more easily degradable compounds in the mass of dead plants, such as cellulose and hemicellulose, are first decomposed, while less degradable compounds (e.g. lignins) can remain in the peat unaltered for decades even when exposed to air (Hyvönen et al., 1996). In addition to cellulose, hemicellulose and lignin, peats contain significant amounts of humic acids, urea and other organic compounds. (Pipes & Yavitt, 2022)

Peat has been mainly used for heating, animal bedding, field fertilization and as a plant growth substrate; to a lesser extent also to manufacture other products. As a substrate, peat is an organic material with a low particle density and high porosity. Due to the source material, slightly decomposed peat has a higher porosity, lower density and higher carbon content compared to other elements. On average, the density of air-dry slightly decomposed peat extracted in Estonia is 0.14 t m^{-3} and the density of well-decomposed peat is 0.22 t m^{-3} (Eesti Turbaliit, 2022). The total porosity of peat reaches up to 80–90%. As the size of peat particles increases, the water retention capacity decreases and the aeration volume increases. Water is available to plants in macro- (100 µm<), meso- (100–30 µm) and micropores (30–3 µm); water in ultramicropores with a diameter of less than 3 µm is not available to plants (Kitir et al., 2018).

Peat production and processing in Estonia

Depending on the weather, the annual volume of peat extraction in Estonia has remained between 0.5 and 1.1 million tons (Figure 1). According to the annual statistics of the Estonian Peat Association, a total of 1.1 million tons of peat were extracted in Estonia in 2022, including 667 thousand tons of slightly decomposed and 433 thousand tons of well decomposed peat (4755 and 1931 thousand m^3, respectively).

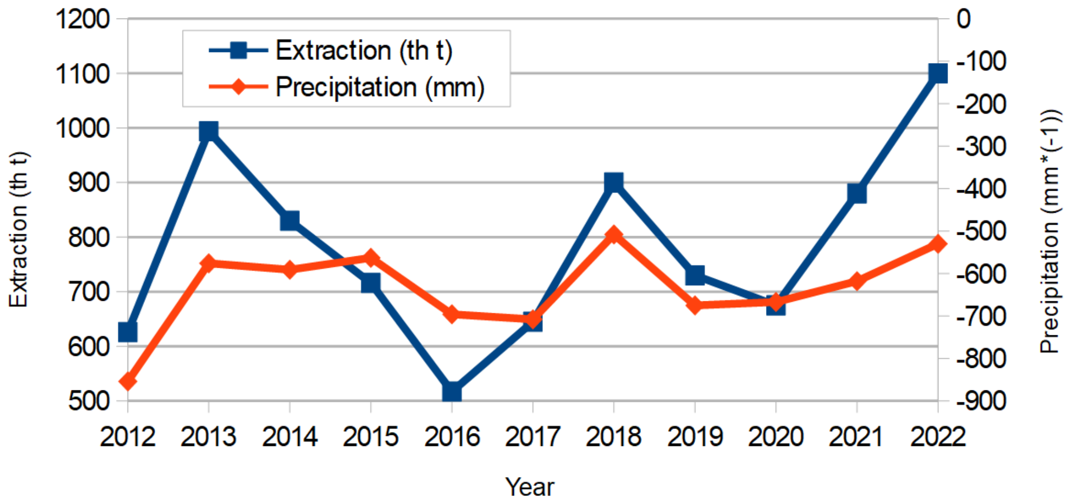


Figure 1. Annual peat extraction and average precipitation in Estonia in 2012-2022. Source: Consolidated Mineral Resources Balance, 2022; Estonian Environmental Agency, 2024.

Horticultural peat of various degrees of processing accounted for nearly 96% of peat products produced in Estonia (Table 1). In previous years, the share of horticultural peat has been even higher, but due to the energy crisis, demand for heating peat has also somewhat increased.

Table 1. Volume of peat products produced in Estonia, their sales in 2022 and the share of the total volume (Estonian Peat Association, 2022)

Product	Processing		Sale	
	Thousand m^3	%	Thousand m^3	%
Growth substrate	1 617	24,2	1 574	25,0
Soil improver	27	0,4	11	0,2
Base substrate	1 324	19,8	1 105	17,6
Milled peat for the production of substrate	3 717	55,6	3 356	53,3
Energy peat			216	3,4
Bedding peat			30	0,5
KOKKU	**6 686**	**100**	**6 291**	**100**

In 2022, 92.9% of the peat products volume produced in Estonia was exported. Taking into account the domestic consumption of energy peat, approximately 203 thousand m^3 of horticultural peat, or 3.2% of the volume of peat products sold, was used in Estonia in 2022. Assuming that the distribution of the decomposition levels of horticultural peat used in Estonia is proportional to the distribution of the total production and that energy peat consisted entirely of well-decomposed peat (both milled and sod peat), it can be assumed that 151.7 thousand m^3 of the horticultural peat used in Estonia was slightly decomposed and 51.8 thousand m^3 was well-decomposed horticultural peat. In addition, 29.7 thousand m^3 of bedding peat was extracted and consumed in Estonia in 2022, which is not directly horticultural peat, but is similar in terms of after-use, as it reaches to the fields as organic fertilizer together with manure.

Properties, constituents and additives of peat substrates

Peat is a porous material formed during the partial decomposition of plant remains under flooded conditions, and is widely used for growing various plants around the world. The production of peat-based growing media began in the 1930s in Great Britain, when Lawrence and Newell began marketing a standardized mixture of peat, sand, and loam. Due to the widespread intensive cultivation of container plants in greenhouses, the use of peat-based substrates spread to other countries in the mid-20th century, including the USA and Canada (Kitir et al., 2018). Although peat extraction began in Estonia at the end of the 18th century, the Estonian peat industry began to produce horticultural peat on a larger scale in the 1970s, when several new packaging factories began operating and the export of packaged horticultural peat gradually increased (Rozental 2012).

Peat is the most suitable substrate for most plant cultures among the available materials: peat retains water and nutrients and gradually releases them to the plants. The pores within it supply plant roots with oxygen, but can bind nearly 20 times more water and oils than its own weight. The structure of peat remains stable even with intensive use and is biodegradable after use. In addition, peat is sterile, light and affordable, supporting safe food production. Since peat itself does not contain much nutrients, it allows to create the most suitable substrate for each plant culture by adding fertilizers.

The main constituents of growing media are materials that provide support to plants and form the bulk of the substrate, which create a suitable physical environment for plant roots and are generally identifiable by visual inspection: peat, composted coconut and wood fibers, perlite, vermiculite, etc. Additives to growing media are substances added to the main constituents of the substrate to support and shape plant growth, which, unlike the main constituents, are added based on a percentage by weight: fertilizers, liming agents, wetting agents, etc. (Kitir et al., 2018)

Main constituents and additives of peat-based substrates

The intended use also determines the composition of the substrate. The chemical, physical and biological properties of the substrate depend on all its constituents and additives. In turn, the price of the substrate depends on them. Therefore, each constituent in the substrate has its own purpose. The positive properties of some constituents can compensate for the shortcomings in the properties of another constituent. Therefore, additives must almost always be added to the main constituents of the substrate. In general, the main constituents are mixed together according to their volume, and additives are added by weight according to the volume of the main constituents.

The main constituents of the growing media are those that make up the bulk of its volume: peat, composted biodegradable waste, bark and fiber, coconut fiber, perlite, vermiculite, etc. In general, their content in the substrate can also be visually detected. Additives are fertilizers, liming agents, buffers, binding agents, wetting agents, hydrogels, chemical pesticides, bioproducts, pigments and other additives that promote the growth of plant and are added to the main constituents; their choice has become very wide in recent decades. Individual substances, e.g. clay, can belong to both, the main constituents and additives, depending on the proportion in the substrate. In general, the content of additives in the substrate cannot be visually determined due to their small amount or physical state (liquid or fine fraction) - this is possible with the appropriate chemical analyses.

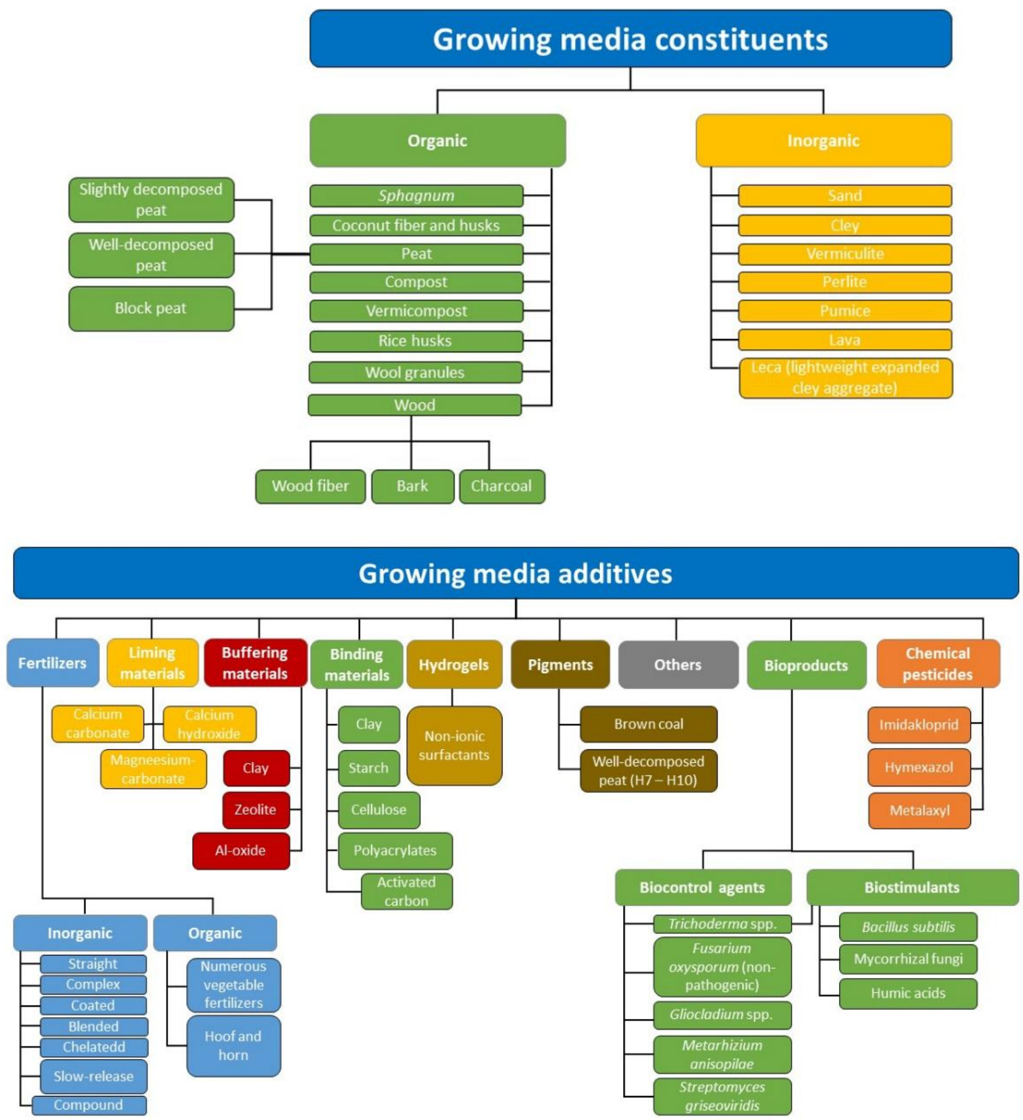


Figure 2. Overview of the main constituents and additives used in growing media (the list does not claim to be complete). Some additives may not always be added to the growing media, but separately during use. [Based on: Schmilewski 2003; supplemented according to the comments from Estonian peat producers].

Fertilizers: Due to the conditions during bog development, *Sphagnum* peat is very low in nutrients. Therefore, all the nutrients necessary for plant growth must generally be added to the substrate. This is usually solved by adding water-soluble complex fertilizers. When adding components, their exact chemical composition must be known in order to achieve a suitable nutrient balance for plant growth. When producing compost-based substrates, their high potassium and phosphate contents must be taken into account, adding sufficient amounts of nitrogen. While adding fertilizers to the substrate, several factors must be taken into account:

- The expected use of the substrate;
- The nutrient demand and salt tolerance of the plant culture;
- The length of the growing season;
- The type and solubility of the fertilizer.

Lime: The purpose of adding lime is to neutralize the acidic substrate; calcium as an element is generally also added to the substrate with it. Although it is possible to use different types of lime, calcium carbonate ($CaCO_3$) is the most common, e.g. in the form of limestone powder or dolomite limestone. Due to their origin and processing, calcium carbonate-based products differ somewhat in their properties. When choosing a lime, the following should be taken into account:

- Type of lime;
- Geological formation and origin;
- Content of alkaline reactive components;
- Hardness;
- Grain size distribution (fraction).

In addition, the amount of lime to be added depends on the properties of other substrate components:

- pH of the main components;
- Degree of decomposition and density of the peat used;
- Content of neutralizable acids;
- Amount and composition of added fertilizers.

The pH of the growing medium is also affected by other factors, such as the properties of the irrigation water, the amount and composition of the liquid fertilizers used, the length of the growing season, and the microclimatic conditions in the greenhouse or field. These factors should also be taken into account when preparing the substrate, if possible.

Buffers: Clay is one of the most widely used nutrient buffers, which has been used in the preparation of growing media in Europe for decades. The pH is generally adjusted with lime, and clays with a low lime content are more suitable for the substrate. Today, clays of very different origins and properties are used in substrates, but montmorillonite-based clays are considered to be the most suitable. In addition to buffering nutrients, clays also help to protect the substrates from drying out and are effective adsorbents of heavy metals. In the majority of clay-containing substrates, its proportion by volume is 2-15%. Based on observations, plants grown in substrates with clay have a more compact form.

Zeolite is a volcanic rock that has nearly 50 different types, which are distinguished by their structures and physicochemical properties. Of these, clinoptilolite with its large internal specific surface area, high ion exchange capacity and stable structure, is considered to be the most suitable for substrates. Compared to bentonite, zeolite has a higher ion exchange capacity and releases nutrients over a longer period of time. Despite that, zeolite is not widely used in growing media.

Aluminium oxide is used to regulate the growth of ornamental plants. Thanks to its phosphorus binding, it improves root growth and plant quality - low phosphorus levels reduce shoot growth and improve root growth.

Binding agents: Many growers use automated transplanters to increase productivity. Especially during periods of low light, root growth decreases and the root ball does not stay together well, making it difficult to use automatic transplanters. Therefore, various substances are added to substrates to keep the root ball together. Clay is well known for its binding properties. Starch and cellulose-based additives can also be used for this purpose, but for several reasons, one must be cautious during the selection and dosage of the binding agent, as it involves several risks: phytotoxicity, air and water deficit, growth of saprophytic fungi in the substrate, negative effects on nutrient availability and adhesion to cell walls.

Wetting agents: Sand, clay and loam are still widely used instead of synthetic wetting agents and surfactants. Wetting agents are divided into anionic, non-ionic, cationic, amphoteric and composite polymers according to the charge of their hydrophilic group. Peat-based growing media are often hydrophobic, especially when dry. Such water-repellent properties result from the waxes, resins and fats contained in the peat, as well as from the voids between and within the peat particles and their "irreversible" shrinkage. Non-ionic additives are best tolerated by plants and are generally not toxic when added in appropriate amounts. However, overdosing can significantly limit plant growth.

Hydrogels: These are synthetic-organic gels based on hydrophobic and water-insoluble polymers that can bind large amounts of water and dissolved substances. Hydrogels were originally developed as hygiene products, but were then also used as soil improvers in desertified areas, eventually finding their way into growing media. After binding water, hydrogels act as reservoirs of water available to plants. Since peat already has a high water-holding capacity, hydrogels are generally not used in peat-based media.

Chemical pesticides: Chemical fungicides or insecticides are generally not added to any standard media. They are added by the grower according to need. In addition, their addition may be regulated by legislation, which varies from country to country.

The addition of bioproducts (e.g. biological pesticides and stimulants) to growing media has increased in recent decades, primarily due to legislative restrictions on chemical additives, to which substrate manufacturers and plant growers have had to look for alternatives. In addition, this is a growing product segment for bioproduct manufacturers, especially in agriculture, but to lesser degree for horticulture. Some products have been successful, others have not. The main problem with them is that their effects are often not proven to be consistent: sometimes they work, sometimes they don't. This can be due to several factors:

- The suitability of the growing media for the microorganism to be colonized (pH, nutrient content, humidity, interactions between microbial organisms, etc.);
- The duration of use and storage time of the growing media;
- Environmental conditions, especially temperature.

The group of biological additives is one of the main additives to growing media, where the need for further development is quite large: finding new and better groups of organisms, developing monitoring and quality control methods, studying the microbial populations already inhabiting the main constituents of the substrates, and the impact of the added groups on the overall community of the growing media produced, as well as the selection and development of materials that carry them.

Pigments: Sometimes additives are also used to give a shade to the growing media. For example, brown coal or well-decomposed *Sphagnum* peat are sometimes used to give a brownish shade to the wood fibers, while at the same time not affecting other properties of the substrate.

In summary, not all of the aforementioned additives are generally used or needed in the substrate. They are only needed if they effectively solve a practical problem.

Constituents and additives in substrates produced in Estonia

The value-adding to extracted horticultural peat begins with sieving and dividing the peat into fractions, followed by additional value-adding. The ready-made peat-based growth substrate accounts for approximately one quarter of the peat products produced in Estonia. Peat, in turn, accounts for 97-98% in them. There are about 15 other substances added to the substrate at the factory, but in total they only account for approximately 2.3% (Table 2) and are mainly used to neutralize pH and increase aeration. However, this is only a small selection of substances used in plant production. Many additives are mixed into the substrate by the plant grower according to the needs of the specific plant culture and the company's recipe.

Table 2. Total quantities of ingredients added to peat mixtures by the Estonian substrate producers (Estonian Peat Association, 2021-2022).

Material	**2021**	**2022**
Organic compounds	**thousand m^3**	
Slightly decomposed peat	741	1491
Well-decomposed peat	861	126
Block peat	27	24
Coconut fiber	5	5
Tree bark	0,3	1
Wood fiber	8,75	10
Compost (from gardening waste)	1,2	2,2
Charcoal		0,4
Inorganic compounds	**thousand m^3**	
Expanded perlite	14,1	10,3
Expanded clay	2,8	1,0
Sand, loam and clay	1,8	5,8
Ground limestone	0,6	2,5
Chalk		0,18
Multimix NPK	0,59	0,09
Expended vermiculite	0,009	
Pumice	1,2	

Additives applied during use

A large part of the additives that directly or indirectly promote plant growth and survival are not added in the substrate factory, but directly during use by the plant grower. In many cases, the plant grower orders milled peat that has been fractioned and neutralized with lime (so-called base substrate), to which he adds additives (e.g. fertilizers in liquid or solid form) himself. The addition of lime is mostly done in factories to ensure efficiency, as it is a voluminous and precise process. Since many additives are used in different combinations in different substrate compositions according to the needs of the plant culture, the approximate content of additives applied on substrates can be estimated mainly based on the needs of the plant cultures and their yields. Statistics Estonia collects data on some additives, e.g. plant protection products (Table 3) that provides a solid overview about their use.

Table 3. Plant protection products used in Estonia mainly for the plant cultures grown in peat-based substrates (Statistics Estonia)

	Tree nurseries		**Flowers and ornamentals**		**Greenhouse vegetables**
	Amount of ingredient, kg	Area applied with the ingredient, ha	Amount of ingredient, kg	Area applied with the ingredient, ha	Amount of ingredient, kg
All plant protection products	**761,74**		**21,86**		**0**
Fungicides ja bactericides	**317,86**		**7,71**		**0**
.. azoxystrobin	24,99	147,36	0	0	0
.. boscalid	36,92	407,78	0	0	0
.. difenoconazole	5,47	312,04	0	0	0
.. fludioxonil	39,73	464,82	0,02	5,43	0
.. penconazole	5,9	345,6	0,3	5,43	0
..propamocarb	16,78	15,57	4,64	5,43	0
. pyraclostrobin	9,26	407,78	0	0	0
.. cyprodinil	59,63	458,57	0,03	5,43	0
Herbicides	**443,61**		**0**		**0**
.. aclonifen	110,3	774,42	0	0	0
.. phenmedipham	98,68	334,54	0	0	0
.. glyphosate	198,68	297,3	0	0	0
..MCPA	31,73	146,73	0	0	0
.. metamitron	2,04	493,26	0	0	0
.. propaquisafop	2,16	63,67	0	0	0
.. rimsulfuron	0,01	154,88	0	0	0
Insecticides and acaricides	**0,27**		**14,15**		**0**
.. alpha-cypermethrin	0	174,25	0,15	5,04	0
.. deltamethrin	0,15	174,25	0	0	0
.. dimethoate	0,12	154,88	0	0	0
.. tau-fluvalinate	0	0	14,01	5,43	0
.. fosetyl aluminum	119,18	58,12	2,71	5,43	0

Although the amounts of substances added to protect plants and to optimize costs are dozed as precisely as possible, some of them may still remain in the substrate after it is used. Therefore, their presence must be taken into account in the further handling of the used substrate.

Water as an additive

High-quality water plays a crucial role in plant cultivation, including the production and use of substrates. It is added to the substrate both to maintain properties suitable for plant growth and as irrigation water during plant cultivation. In factories located in Estonia, peat-based substrates are also irrigated with water, because they become hydrophobic when dried out and therefore unsuitable for plant growth. Similar to the rest of the substrate, the added water must be free of pathogens and additives unsuitable for plant culture. The pH of the water is also important, as it affects the reaction of the rest of the substrate. Since the optimal pH level for the majority of cultivated plant cultures is between 5.5 and 6.5, the use of calcareous groundwater as irrigation water is limited. Therefore, in some countries, irrigation water needs to be transported over long distances, even by importing it.

Bedding peat

Peat has played an important role as animal bedding, especially in regions and during periods when the availability of other suitable materials is limited. Due to its antibacterial properties, peat bedding is still a valued material in broiler farms, horse stables, sheep, dairy, beef and pig barns. For example, in Finland, 22% of pig barns use peat bedding. In addition to its antibacterial properties and physical well-being, peat bedding has several positive properties, e.g. as a dietary supplement it significantly reduces the risk of anemia in piglets, has an extremely good liquid binding capacity (1 m^3 for 500-800 l of liquids), is warm and fluffy, acidic (pH ~3.5-5: not optimal for pathogenic substances) and also binds ammonia and hydrogen sulphite. Disadvantages include dark color (looks "dirty"), dusty when spread, can be of variable quality, and can freeze when wet in winter. In Finland, the long-term use of peat as bedding has minimized the need for antibiotics, while the incidence of campylobacter (the main cause of human gastrointestinal infections in the EU) in broiler flocks is more than 10 times lower than the EU average (2.5% vs. 27.3%). (Suojala, 2023)

Alternatives to horticultural peat

Peat is the most suitable substrate for growing many plant cultures, but in order to diversify the choice of substrate, find a possible better and cheaper substitute, mitigate the risk of peat supply security and reduce the environmental impacts of peat production, in parallel with the widespread use of peat substrates, alternatives to peat have been sought in recent decades, and in some countries (e.g. Great Britain) attempts have also been made to limit the use of peat substrates in hobby gardening.

The most important advantages of peat are its structure and sterility: due to its formation, peat is free from pathogens and pests, and controlled production is also free of weed seeds; the low nutrient content allows for the addition of fertilizer in the right amount for the respective plant culture; the cellular structure with its large vacuoles that stores water and air ensures high water capacity with a simultaneous high air volume.

Peat moss, which has not yet become peat, has the most similar properties to peat, and attempts to grow it industrially have been made in various countries (especially Germany) in recent decades. As a new material, its production is limited primarily by the lack of sufficient experience and its slow growth compared to the need for the material, which would require industrial cultivation on very large areas of land to replace peat (substrate manufacturers estimate that, for example, to cover the needs of Germany alone, peat moss would need to be grown on at least 65,000 hectares). Depleted peat production areas, where the water level has been raised close to the ground, would be particularly suitable for this. Unfortunately, the same areas are also most suitable for restoring near-natural bogs.

Also, as a light, well-wetting, with good water and air capacity, and renewable material, **coconut fiber** has been considered one of the best peat analogues in growing substrates. However, its biggest disadvantage is the high concentration of salts contained in the raw fiber that are toxic to plants, which, when washed out multiple times, results in a high consumption of fresh water, also posing a risk for drinking water pollution. While in the case of the natural cycle, the nutrients contained in coconut fiber (especially K and Mg) would return to the soil, in the case of substrate production, the nutrients are removed from the respective ecosystems. In addition, coconut fiber is very susceptible to certain fungal diseases and must be transported to Europe mostly from India and Southeast Asia. The availability of coconut fiber is limited due to its other uses (especially the filter industry) and the seasonality of raw material harvesting. The price of coconut fiber is also increasing with demand.

Due to the development of the circular economy worldwide, **compost produced from garden waste** has increasing potential as a renewable resource and also as a growth substrate. In the case of compost, it is important to emphasize that professional gardening uses exclusively plant waste compost, because compost made from biowaste may contain dangerous pathogens. The advantages of compost are the recycling of garden waste (e.g. leaves, discarded plants) and both the advantage and disadvantage is its high nutrient content. Successful composting reduces the number of pathogenic organisms in the substrate. However, due to the high pH and high nutrient content (especially K and P), compost cannot generally be used in its pure form, but must be mixed with other materials, usually peat; therefore, compost is generally used in relatively small quantities in substrate mixtures. Although industrial composting kills pathogens relatively effectively, the risk of plant diseases and pests still remains in the compost. Compared to the previous constituents, the proportion of mineral matter in compost is high and the substrate itself is denser and heavier, affecting transport costs and thus increasing environmental impacts. Due to the scarcity of high-quality raw materials, the availability of compost is also limited, and from a carbon sink perspective, the collection of plant material used for composting means carbon transfer – the input of organic carbon into the soil at the collection site decreases and it is transferred to the area where the compost is used.

Tree bark is also a renewable resource and has a stable and well-aerated structure, but it does not retain water well and its nitrogen buffering capacity is low. In its pure form, it is suitable for use in growing epiphytes (e.g. orchids), but is more suitable for substrate mixtures for other plants in small proportions; if the content is too high, it has a negative effect on plant growth. To prevent the spread of nematodes that threaten plants, tree bark also requires additional processing before being added to the substrate. The availability of suitable tree bark is also limited, because the only the bark of certain tree species is suitable as a substrate**.**

Wood fibers have similar properties and they are added to substrates to increase aeration, but their water retention capacity is low and they are generally not used in their pure form. In the case of used in higher proportion, nutrients, especially nitrogen, must definitely be added to the substrate. Wood fiber decomposition is very fast (under favorable conditions, up to 50% of the original mass within half a year), and therefore such a substrate quickly loses its plant growth-supporting properties and greenhouse gas emissions are high (Veeken, 2003; Verhagen et al., 2009). The use of wood fiber also increases the risk for the spread of harmful nematodes.

Perlite is sterile, does not collapse or decompose, is reusable and aerates the substrate well. At the same time, it does not retain water well. Since the raw material for perlite is volcanic rock, it is not renewable and the production of perlite is very energy-intensive.

Similar to compost, **rock wool** is also predominantly made from secondary raw materials and is free of plant diseases at the beginning of use, but its production is very energy-intensive. The use of rock wool and water solutions is very effective, because all nutrients are immediately available to the plant, but it requires thorough prior knowledge. The use of the material damages people's respiratory tracts and therefore requires personal protective equipment from plant growers.

Thus, each substrate component has its own advantages and disadvantages in terms of both usage properties and environmental impacts. The overall maximum quantity and availability of materials in the world must also be taken into account, because in addition to the substrate industry, other industries also need them. Based on a study by professor Chris Blok et al. (2021), if current trends (human population growth and rising living standards, reduction in fertile farmland, increasing popularity of plant-based foods, etc.) continue, the annual demand for substrates in the world may increase to 283 Mm^3 by 2050, i.e. more than four times compared to 2017 (67 Mm^3) (Figure 3). According to their forecast, the use of growing substrates in food production will increase by 260% and in ornamental plant cultivation by 490%. Most authors of works comparing the possible components of growing substrates and assessing their availability have come to the conclusion that there is currently and in the near future no viable alternative to peat as a basic component of growing substrates. It is also important to note that even for crops that can be grown in alternative substrate components, the use of peat for pre-growing small plants is generally unavoidable. Although the peat content in substrates is decreasing on average, the need for peat is generally increasing because the need for substrates is increasing even more (Figure 3). Since the main functions of the substrate are based on peat, it can be said that even due to the relatively lower content of peat in mixtures, its importance increases, because even larger number of plants can grow thanks to peat.

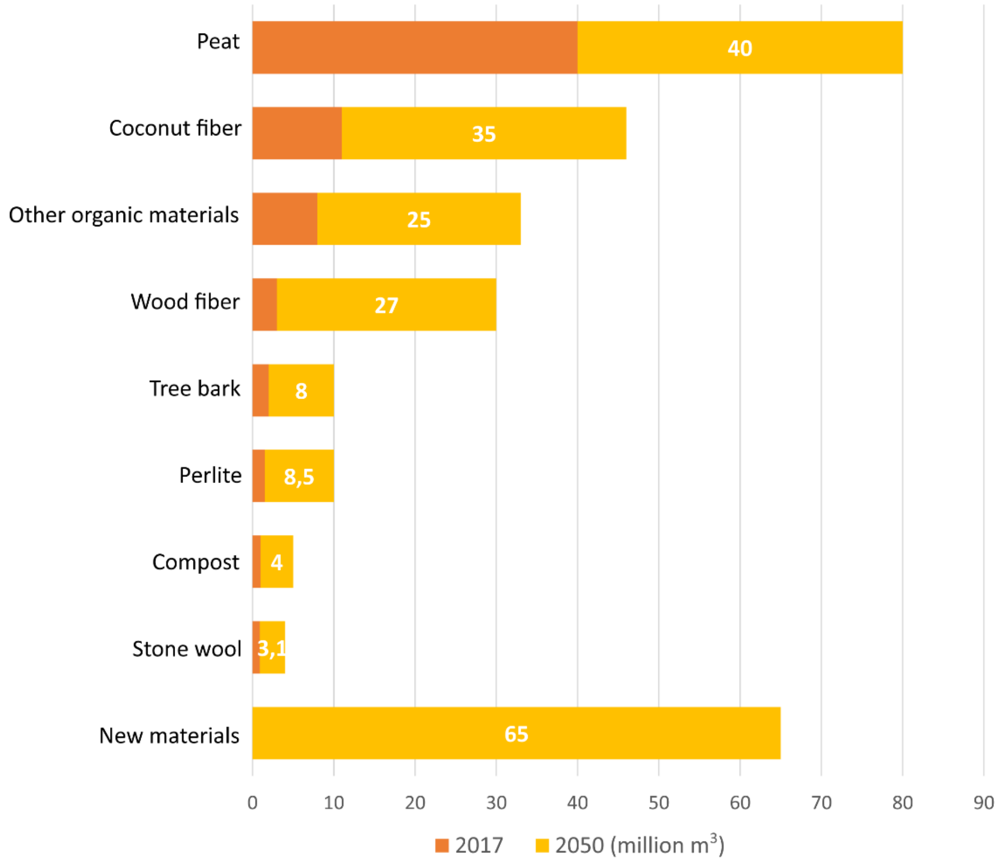


Figure 3. Global annual use of major growing media constituents in 2017 and forecast for 2050. [Based on: Blok et al., 2021].

For many plant cultures, it has been found that if you want to reduce the proportion of peat in the substrate, it is better to grow the plant in a substrate with a low peat content and transplant it into a similar substrate than to transplant a plant grown in peat into a substrate with a low peat content (HortWeek, 2024a). Also, in a peat-free substrate, the plant may need to change the substrate more frequently. For example, when growing *Sarracenia* in peat, the substrate needs to be changed every 8-9 years on average, while a peat-free mixed substrate (1/3 pine bark, 1/3 peat moss and 1/3 cork granules) needs to be changed after every two years (Hortweek, 2024a). It is also generally known that peat-free substrates require more watering and fertilization (Hortweek, 2024b). One Estonian perennial grower also noted that when he used wood chips with peat in a certain proportion instead of pure horticultural peat, the need for fertilizer increased by 30%, especially for nitrogen. Another perennial and young plant grower said similarly that, considering plant health and quality, he does not see an alternative to peat, at least for potted plants. The story is different with exotic houseplants, in which growers and dealers prefer coconut fiber and perlite instead of peat for the majority of plants. Indeed, they are not grown industrially in Estonia, and the climate and soil of the plants' homeland are different from Estonian conditions.

Plant diseases and parasites

The main types of plant diseases are rots, wilting, spots, pads or pustules, scabs, secretions, mummification and premature leaf fall (Albert, 2018). The main reason for changing the substrate in greenhouses is the spread of plant diseases. In unheated greenhouses, pests are not a problem in Estonia (although aphids and greenhouse whitefly may occur). When humidity remains high, the most common diseases in greenhouses are noble rot, tomato blossom end rot and tomato leaf mold, stem rot, Peronosporales, powdery mildew and white rot. Although several plant protection products are used, there is still a high risk that plant diseases will reduce plant survival, growth, and yield.

Use of peat in the horticultural sector

Horticultural peat is the most important substrate used in the horticultural sector, where both the mature plants for the end consumer and young plants are produced. The latter will in addition to the horticultural sector itself move on to the agricultural sector. The value of plant production in Estonia accounts for 41-51% of the total value of the agricultural sector, of which the value of horticultural production accounts for 11-18% of the value of plant production (Statistics Estonia, 2022).

Survey: Use of horticultural peat in Estonia

To find out the volumes, practices and plant cultures grown in horticultural peat, statistical data collected by various institutions were combined with the results of a survey conducted among Estonian plant growers in the spring of 2023 (the questionnaire is presented in Appendix 1). Plant growers who responded to the survey were selected to have all the main plant groups grown on peat substrates represented. In addition to Estonian plant growers, people involved in various parts of the peat substrate supply chain were interviewed on April 5, 2023 in the Netherlands, which is the largest export market for Estonian peat producers:

- Arjan Zwinkels – Kekkilä-BVB De Lier substrate plant, product development manager;
- Esther van Geest – Geest Potplanten, ornamental plant grower;
- Marco Zevenhoven – RHP operational director.

In addition to plant growers, retailers and wholesalers of substrates and plant cultures grown on them, peat producers and botanical gardens were interviewed or data required from them in Estonia.

Forest seedlings

According to the Plant Health Register, 38.5 million forest seedlings were grown in Estonia in 2022 (Table 4), more than half of them in the nurseries of the State Forest Management Centre (RMK) (22 million), which is close to the long-term average. In addition, 4.4 million seedlings were imported. Of the forest seedlings grown in Estonia, 85.5% were conifers and 58.3% were potted plants. The forest tree seedlings were grown in 2022 on 12.63 ha, including 8.35 ha area under potted plants.

Table 4. Forest tree seedlings produced and marketed, exported or imported from Estonia in 2022 (thousand trees; data: Plant Health Register, 2022)

Thousand trees	Produced and sold in Estonia			Export			Import		
Tree species	**Bare-rooted**	**Potted**	**Total**	**Bare-rooted**	**Potted**	**Total**	**Bare-rooted**	**Potted**	**Total**
Silver birch	3655	1309	4964	0	43	43	198	85	282
Norway spruce	11265	6206	17472	0	316	316	2276	1240	3516
Scots pine	739	14060	14800	0	320	320	193	327	520
Black alder	385	104	489	0	1	1	16	0	16
Hybrid larch	0	21	21	0	0	0	54	0	54
Curly birch	0	5	5	0	1	1	0	0	0
Hybrid poplar	0	5	5	0	56	56	0	0	0
Small-leaved linden	0	0	0	0	1	1	0	0	0
Douglas fir	0	0	0	0	0	0	3	0	3
Wild cherry	0	0	0	0	0	0	0	1	1
TOTAL	**16045**	**21710**	**37755**	**0**	**738**	**738**	**2739**	**1652**	**4391**

On average 5,775 m^3 of peat is used annually in Estonia for growing forest tree seedlings. All potted seedlings are grown on Estonian peat substrates (mostly 5 m^3 large bales), but on very different mixtures and fractions, including crushed block peat substrates. The exact composition of the mixture depends on the tree species, but the subsequent planting site (forest site type) is not taken into account when mixing the substrate. Limestone flour is mainly used to neutralize peat mixtures. The purchased substrate must contain fertilizer (on average 1.0 kg/m^3, for example PG MIX 12-14-24) and wetting agents (e.g. Fiba-Zorb). To a lesser extent, longer-acting fertilizers are also used in the substrate, for example Osmocote 3.4 M or Plantacote Pluss 4M 2kg/m^3. Either vermiculite, sand or sawdust is used to cover the seeds. During the pre-cultivation of seedlings, the temperature in the greenhouses is mostly 15-20°C, and the humidity is not separately controlled.

Peat is generally used quickly, i.e. within a few weeks. The remaining quantities are small and are used up within six months. According to the nurseries, there were no direct obstacles to the reuse of the peat substrate, and the weed-seeded mixtures were also used up in the lower layers of the pots. Since 95-100% of the substrate moves with the plant to the end user, no significant amount of the used substrate remains. The substrate remains in the soil with the planted seedling.

Vegetables

Vegetables are grown in Estonia mainly in the open field (e.g. cabbage, carrots) or hydroponically in greenhouses (industrial tomato cultivation). In Estonia, greenhouse vegetables are grown in greenhouses on a total of approximately 87 ha, of which tomatoes account for nearly 2/3. The vast majority of greenhouse vegetables are grown in households. (Statistics Board, 2023)

In addition to growing vegetables, large vegetable plants need to be pre-grown from seed in the Estonian climate. For example, growing cucumber and cabbage plants requires approximately 70 cm^3 of peat substrate per plant, in which the young plants germinate for 1-1.5 months. Many Estonian vegetable growers have pre-grown plants in their greenhouses, after that they are planted in open ground in the spring. Therefore, it is logical that all the used substrate is also transferred to the field. For some crops, e.g. tomatoes, intermediate replanting may be necessary. Peat mixtures (pH 5.6-6.5) are used as the substrate, to which fertilizer (N, P, K) and chalk are added. Plants are also sprayed species-specificly with various synthetic and biological substances to control diseases and pests, which may also partially remain in the used substrate.

Perennials and summer flowers

Flowers are generally grown in 1-liter pots with an average peat consumption of 930 cm^3. Both poorly and well-decomposed peat (average pH 5.5-6.0) is used as a substrate, to which clay and/or perlite and long-term fertilizer are added depending on the culture. Summer flowers grow in pots for 2-3 months before being sold, poinsettias for 5-6 months, and some perennials (e.g. peonies) for up to 9 months. Some gardeners also sell 1-5 cm cassette plants, which are intended for further cultivation. Plants grown include irises, carnations, lobelias, begonias, fuchsias, dahlias, broken hearts, etc. Depending on the year and culture, an average of 5% of the plants remain unsold or are discarded for other reasons - many cultures remain representative for a short time. Both the plants themselves and the substrate usually go into compost and are generally not reused in potting - it goes into landscaping and filling holes.

Ornamental and fruit trees and bushes

It takes 4-5 years to grow ornamental and fruit tree seedlings in nurseries. After 2-3 years, the seedlings are potted into larger pots, usually 7-liter pots (due to compaction, the peat consumption is somewhat higher). The substrate is not changed, but more peat is added to the initial volume. Generally, slightly decomposed peat is used, but also different mixtures, screened fractions and crushed block peat are also used depending on the plant. The pH of the substrate is 3.5 to 6.0 depending on the seedling type - in the case of a higher pH, limestone flour is used for neutralization. Basic nutrients, Osmocote fertilizer and stabilizers are added to the peat. Over 95% of the peat used in nurseries is sold to the end user with the seedlings. In the case of growing in a greenhouse, specific replant disease occurs in a year in the case of monoculture, but in two years when, for example, apple and plum are grown alternately, the substrate is then composted and transferred to the field. However, the use of the little volumes of peat left over varies in different nurseries: the remaining peat is generally used in potting larger trees or, after composting, goes to the field or into urban landscaping. Cultivated crops include pear, apple, plum and cherry trees, various ornamental trees, raspberry, currant and gooseberry bushes.

Herbs and salad

For the cultivation of herbs and salad, a mixture of slightly decomposed and well decomposed peat in a ratio of 70/30 (pH 5.5-6.0) is mainly used, which is sold in a pot together with the culture being grown to the end consumer. The moisture contained in it ensures a longer survival and use time of the plant. On average, 70 cm^3 of peat is needed to grow one herb or salad plant and only basic nutrients are added to the substrate. The plants grow quickly, which is why the use time of peat is only 1.5-2 months. In greenhouses, the average temperature is 16°C and the humidity is 75%. Since the substrate moves with the plant, only a minimal amount of peat remains to the plant growers, which is added to compost and/or ploughed into the soil. Due to the risk of pests and diseases, substrates that have already been used once are no longer used to grow new plants. The end-product is no longer watered in stores and remains saleable for up to two weeks. The substrate left in stores, after exceeding the expiration date and in households after the plant is consumed goes either to a composting site among biowaste or to a home compost bin, or in the worst case, to household waste.

Biological control is also used in Estonian gardens, primarily with mites. In Grüne Fee, the largest producer in Estonia specializing in the production of herbs and lettuce, the biological control agent ENTONEM, which contains a parasitic nematode (*Steinernema feltiae*), is mixed into the peat for the plants to control the midge larvae. The nematodes penetrate the organism of the midge larva and begin to develop there, using the larval tissues for nutrition. As a result, the larva dies within a few days. The natural product GlioMix, which consists of filaments and spores of the *Gliocladium* fungus, is also mixed into the peat. Gliomix promotes the reproduction of microorganisms important for plants in the growing substrate, improving root growth and protecting plants from diseases.

Salad and herb plants sold in small peat pots in retail trade are no longer watered in the store and are kept there for a few weeks. However, the share of write-offs in this category is very small, about 0.2% (some products are higher, others are lower).

Exotic houseplants

A separate group of plant cultures are exotic houseplants: anthuriums, philodendrons, monsteras, clematis, waxflowers, succulents, cacti, etc. In the case of exotic houseplants, the composition and duration of use of the substrate and the size of the growing pot vary greatly depending on the culture. In Estonia, they are grown and propagated on site for sale in very small quantities, with almost no peat being used for this purpose. Instead, more coconut fiber is used (10-15% of the substrate total volume), which, according to plant growers, has a better water retention capacity. In addition, expanded clay, perlite, wood fiber and bark, and other components are used in substrate mixtures. However, peat exported from Estonia is widely used, for example, in Dutch greenhouses to grow exotic houseplants.

Botanical gardens

There are two larger botanical gardens in Estonia, the Tallinn Botanical Garden and the University of Tartu Botanical Garden, which also use peat substrates to a considerable extent to grow the plants in their collections. Peat is used there both for pre-growing plants and mixing into the substrate, as well as to cover the soil of acidic plants, bulbous flowers and perennials, including as a winter cover. The usage time of the substrate varies from a few months to years, the surpluses are recycled through the composting field or mixed with the soil. Both botanical gardens use both natural milled peat (mainly for covering perennials and as a soil conditioner, a total of 170 m^3 per year on average) and various peat mixtures for pre-growing plants and mixing them into pots. The main products used for this purpose in both the Tallinn and Tartu University Botanical Gardens are Kekkilä horticultural peats (Flower Soil, Summer Flower Soil, Tomato Peat, Organic Tomato Peat, OPM 540W), a total of 113 m^3 per year. Natural milled peat is used more in open ground, while horticultural peat is used in greenhouses, from where it is sometimes planted to the open-air flowerbeds. Block peat has also been used to border the exposition. The area of the UT Botanical Garden is 3 ha, and there are 0.07 ha of greenhouses with different climates. The area of the Tallinn Botanical Garden is 22 ha, including 0.20 ha of greenhouses.

Mushrooms

Although growing mushrooms on peat substrate is common in the world, in Estonia, mushrooms are grown in industrial quantities on residues from the wood industry (sawdust) and grain harvest (straw), as well as on tree stumps and logs. In 2019-2022, Leovander Grupp also grew champignons in Lääne-Virumaa (north Estonia) under the Natu'ke brand, but its substrate came from the Netherlands. However, it is worth noting that the old substrate was sent for recycling, but there was also a plan to use it as fertilizer in the fields. The Ministry of Agriculture also recommends in its publication "Abiks seenekasvatajale" (Kukk, 2005) to use milled peat as a covering material for mushroom crops when growing both champignons and stropharia, either mixed with limestone dust or humus (compost soil).

Bedding peat

Bedding peat is not directly horticultural peat, but since its properties and subsequent use are similar to horticultural peat, it is also relevant to discuss bedding peat in this study. In 2021, 19.4 thousand m^3 of bedding peat was sold in Estonia and in 2022, 29.7 thousand m^3 of bedding peat was sold and fully used in Estonia (Estonian Peat Association, 2022).

Similarly to used horticultural peat, the vast majority of used bedding peat mixed with animal manure also ends up on fields as organic fertilizer. There, it can support plant growth significantly more than many other plowed-in additives (e.g. straw). The quality of organic additives is largely determined by the carbon to nitrogen ratio (C:N ratio), as it is related to how quickly the used organic nitrogen becomes available to plants as mineral nitrogen. When organic matter decomposes, soil microorganisms use N for enzyme production and growth, which can lead to N immobilization in microbial biomass if the C:N ratio of the organic matter is too high. To decompose low-quality organic matter, such as straw, which has a C:N ratio of around 100, soil microbes require all the nitrogen contained in the organic matter. In addition, soil microbes remove nitrogen from the soil solution, which mineralizes to the soil from the organic matter, leaving little or no freely available nitrogen in the soil. Used bedding peat with manure, as well as composts with a C:N ratio of around 10, contain relatively more nitrogen than soil microbes need during decomposition and thus increase the availability of mineral nitrogen in the soil. (van der Sloot et al., 2022)

Imported plants

Some plant cultures are grown in Estonia to a small extent and are mostly imported from other countries, although they may have been grown on Estonian peat. For example, strawberry plants grown in Estonia often come from Poland or the Netherlands; some plant growers also grow their own plants. According to the interviewed RHP representative, it is possible to reuse 5-10% of the substrate used in strawberry cultivation without reducing yield or endangering plant health.

Other peat uses

Horticultural peat is also used for purposes that cannot be directly associated with a specific plant culture or in cases when peat is not the main substrate. These include various landscaping, mulching garden plants, mixing in compost, using it as toilet peat, etc. It is also impossible to find out more precisely what the buyer has used it for in the cases when the substrates are purchased from retail stores. However, wholesalers have estimated that approximately 45% of peat substrates sold are intended for garden cultures and 55% for flowers and houseplants, with the total retail volume of horticultural peat being approximately 8,900 m^3.

Estimation of peat substrate usage volumes

Data are not collected on the specific uses of horticultural peat produced and used in Estonia, therefore it can only be estimated indirectly based on the amount of plants grown, the amount of substrate required for this, companies turnover and identified usage practices (Figure 4). The fact that larger companies often grow different plant groups in parallel (e.g. fruit trees and bushes, perennials, summer flowers, etc.) also complicates the assessment.

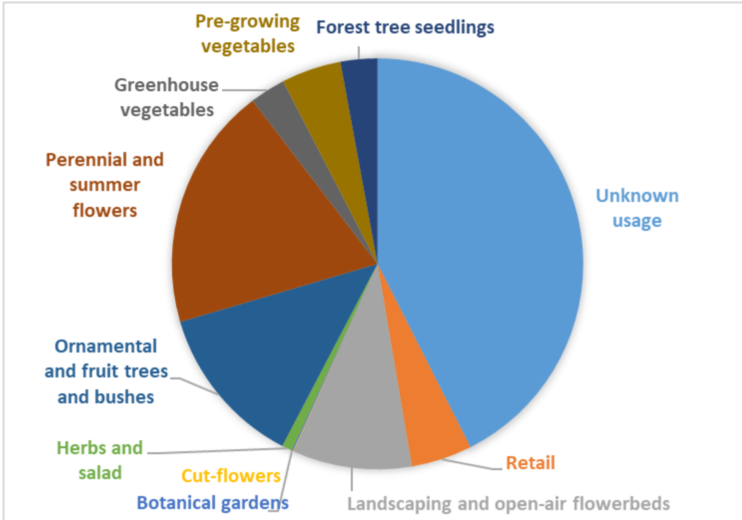


Figure 4. Estonian estimated domestic percentage distribution of horticultural peat uses based on 2022 data with a total volume of 203 thousand m^3.

It is even more difficult to determine this in Estonian export markets. However, several horticultural and peat production experts in Estonia, Finland and the Netherlands agree that the volume of peat substrates is divided more or less in half between food and ornamental plants in the target markets of growing substrate. However, such a domestic consumption distribution does not mean that substrate imported from Estonia is also used in a similar proportion. During the survey conducted among Estonian peat producers, they were also asked to assess the areas of use for which their customers use the supplied (2021-2022 seasons) gardening peat. Since there may be additional links in the supply chain and the plant grower may also have several areas for which the substrates are used, many peat producers were unable to assess this. However, the responses received showed that more than 4/5, or the overwhelming majority, of the horticultural peat produced in Estonia and exported from here is used for growing vegetables (especially young plants) (Figure 5).

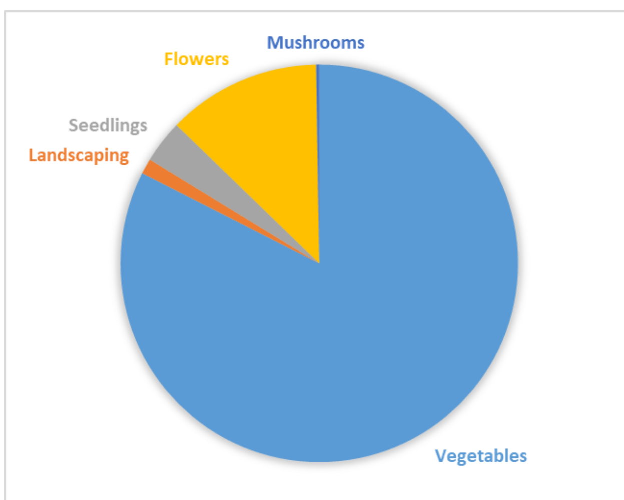


Figure 5. Estonian peat producers' estimate of the intended use of exported peat in 2022.

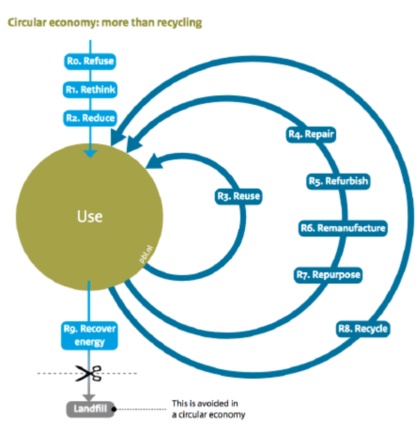
A follow-up study of global substrate use and projected demand began in 2024, with preliminary results indicating that 105 Mm^3 of growing media was used worldwide in 2022, the majority of which was peat (Table 5). The vast majority of the substrate was used for food production.

Table 5. Global use of growing media in 2022 (Nguyen, Barbagli and Blok, 2024). The results are preliminary and may change during the study.

Region	**Area under substrate (kha)**			**Champignon production (Mkg)**	**Substrate volume (Mm^3)**				
	Food plants	Orna-mentals	Tree nurseries	Mushroom on substrate	Food plants	Orna-mentals	Tree nurseries	Mushroom on substrate	Retail consumption
N-America	10,0	6,0	28	440	2,0	1,8	11,2	0,4	13,7
S-America	2,6	3,2	3		0,5	0,9	1,1		
Europe	37,0	12,4	20	1162	7,4	3,7	8	1,2	19,6
Africa	4,8	1,2	0		1,0	0,4	0,00		
Middle-East	5,6	1,9	0		1,1	0,6	0,03		
China	19,7	1,9	13	13629	3,9	0,6	5	13,6	
Asia (without China)	18,2	4,6	4	74	3,6	1,4	2	0,1	
TOTAL	**98**	**31**	**68**	15306	**20**	**9**	**27**	**15**	**33**
	197			**15306**	**105**				

After-use and circular economy

The European Commission has defined the circular economy as an economy and way of thinking that aims to preserve the value of products and materials for as long as possible. Waste is generated and resources are used as little as possible, and when a product reaches the end of its life cycle, it is used to create new value.



R0 keeldumine *(refuse)*
R1 ümberkujundamine *(rethink)*
R2 vähendamine *(reduce)*
R3 korduskasutus *(reuse)*
R4 parandamine *(repair)*
R5 renoveerimine *(refurbish)*
R6 taastootmine *(remanufacture)*
R7 kasutusotstarbe muutmine *(repurpose)*
R8 ringlussevõtt *(recycling)*
R9 energiakasutus *(recover energy)*

Figure 6. Circular strategies defined by the Dutch Environmental Impact Assessment Agency (Planbureau…, 2018) that can be used to create a circular flow of products and materials (see also Eljas-Taal et al., 2019).

Table 6. Circular strategies with examples of used horticultural peat

	In Estonian	In English	Examples about using horticultural peat
R0	Keeldumine	Refuse	Peat-free substrates, hydroponics, aeroponics, no-substrate use
R1	Ümberkujundamine	Rethink	Using substrates with different properties and compositions in different layers
R2	Vähendamine	Reduce	Smallest possible amount of substrate with least possible peat, re-evaluating the need for plant growth
R3	Korduskasutus	Reuse	Using the same substrate with different plants if possible. Generally, after using in a greenhouse, they are transferred to open land (fields, urban landscaping, open-air flowerbeds).
R4	Parandamine	Repair	Reuse after composting or sterilization
R5	Renoveerimine	Refurbish	-
R6	Taastootmine	Remanufacture	Takeback of used substrate by the substrate factory, used peat as part of a new substrate mixture
R7	Kasutusotstarbe muutmine	Repurpose	Using used substrate as a raw material for a new product, e.g. for the production of insulation material, activated carbon or biochar.
R8	Ringlussevõtt	Recycling	As a toilet peat
R9	Energiakasutus	Recover energy	Using used peat substrate as energy peat

The value of peat substrates lies in their physicochemical properties, such as porosity and water retention capacity, sterility, high carbon content, etc. Other substances added to peat substrates during primary use (fertilizers, plant protection products, etc.) can be both positive and negative in their subsequent use. On the one hand, residues of fertilizers and plant protection products contained in the used peat substrate can also support plant growth in the field or in urban landscaping, where the used substrate is transferred during after-use. On the other hand, the nutrients contained in the substrate increase its further decomposition, and residues of plant protection products can also be somewhat harmful to pollinators and other biota. However, optimal amounts of fertilizers and plant protection products are generally used in plant production, which is why their residues are likely to be minimal in the used substrate and therefore their potential impacts are small.

Alternatives for the after-use of peat substrates and their part in carbon cycle

The main already used and potential options for the peat substrates after-use identified so far during the study, which are sometimes combined with each other, are:

1. Substrate reuse
2. Planting in the soil with the plant
3. Composting
4. Use in landscaping
5. Addition to agricultural soils as a soil improver
6. Use in quarry reclamation (potential)
7. Use as a raw material for alternative products (potential).

In addition to the changes in the carbon content of peat during and after the use of peat substrates, it is important to also take into account the impact of plants growing in the substrate and other factors on the overall carbon dynamics, including when comparing them to alternative substrates and taking into account substances added to peat mixtures.

In the case of most growing substrates, at the end of the life of the used growing media (End of Life - EoL), its after-use is generally composting or use as a soil improver in the field. Although the majority of the substrate remains after its use, the approaches currently in use (e.g. Growing Media Europe, 2021; Stichnothe, 2022; Paoli et al., 2022) assume that the carbon remaining in the peat at the EoL is completely oxidized and the carbon emissions are reported in full at the EoL stage. Growing media used for composting or as a soil amendment is considered residual material, unless the value of the substrate is higher than the cost of collecting it - in that case an economic profitability analysis is applied. The residual value is attributed to the used growing media that is composted or used as a soil amendment. No impact from the production of the growing media (e.g. peat extraction, coconut fibre harvesting) may be attributed to the composting or the after-use of already used growing media as a soil amendment. In addition, the composting or further processing of growing media is considered to be an economic activity separate from the system under study (production of horticultural peat). This means that the impact of composting (including collection) or further processing cannot be attributed to the life cycle of the growing medium (Growing Media Europe, 2021). However, these impacts can be taken into account when choosing the primary substrate and its subsequent use. This kind of approach is associated with a high generalization and does not take into account the real carbon cycle, where different substrates decompose at different rates, affect the properties of the soil differently when introduced into the soil, and increase the accumulation of additional underground and aboveground debris and the rate of humification during secondary bioproduction in different ways.

Substrate reuse

The survey results showed that when changing plant cultures, e.g. apple trees and then plums, it is possible to use peat substrate several times without additional treatment. Since many diseases and parasites are specific to the plant crop, it is possible that when changing the plant culture, the risk of pathogens may not harm the plant even if the substrate is contaminated with them. However, since plant growers invest a lot of time and energy in plant cultivation, and seeds are expensive, people generally do not want to risk with the quality of the substrate (Schmilewski, 2008).

When replanting ornamental and fruit trees into larger pots, some plant growers use last year's substrate in the bottom layers of large pots. Both RHP and Kekkilä-BVB representatives pointed out that 5-10% of the total volume of peat used for growing strawberries can be reused, but this still requires some treatment - which treatment method is most suitable is still being investigated through experiments. However, it is known that if peat is heated above 45°C (or it self-heats in the pot), it can become harmful (toxic) to plants. Steam treatment of the growing medium has been successfully tested in the cultivation of chrysanthemums (Vandecasteele et al., 2020). However, the possibilities of immediate reuse of the growing medium for growing new plants during the following year are very limited. Still, reuse does not significantly affect the use and impact of the material leaving the circulation, but mainly affects the need for primary raw materials (substrate constituents). Today's extraction volumes already take this into account through market demand.

Planting in soil with a plant

Planting the substrate surrounding the roots of the seedling in soil with the plant is one of the most common practices for using and reusing horticultural peat. Plants sold in potted peat medium are mostly planted together with the substrate surrounding the roots, either in home gardens, plantations, greenhouses, public spaces or forest soil. However, it is important to assess the effect of peat substrates on the growth and photosynthesis (carbon sequestration) of plants growing in the respective substrate, as well as how peat carbon behaves in these soils. In general, it has been found that the carbon content in the soil remains in accordance with the natural carbon content specific to the specific soil type. If the soil has depleted of organic matter during intensive cultivation (the vast majority of cultivated land in both Estonia and Europe; LUCAS 2018), then peat added to the soil with the root ball of plants or as a separate soil improver contributes to the restoration of the density of the humus horizon and carbon content until a natural equilibrium state is reached. In this case, the degree of peat carbon retention in a 100-year perspective can be about 30% of the original carbon content (Kauer & Astover, 2024), and when planting container plants in peat soil with peat substrate, a carbon content similar to the surrounding peat soil (40-50% C) is retained.

If cultivated land has lost some of its humus and organic carbon content during intensive management, its recovery through natural processes occurs slowly (Figure 7), but the addition of residual peat/peat compost or plant root ball to the soil helps to accelerate the recovery of soil carbon reserves to a specific soil humus storage capacity. In Figure 7A, the curve Management A can be used to describe, for example, the addition of plant compost, which gives a rapid initial effect, but at the same time, due to faster decomposition (and higher CO_2 volatilization), a lower final result in terms of soil carbon content than a peat substrate with slower decomposition (Management B).

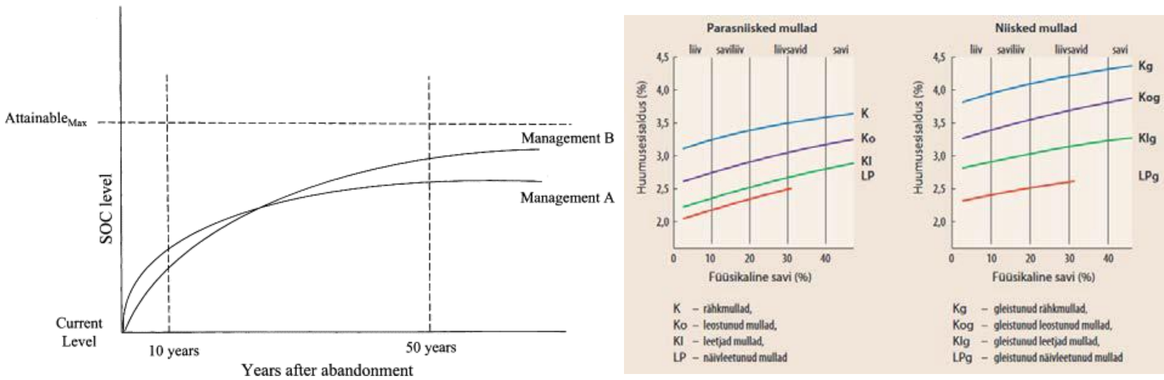


Figure 7. Use of different management techniques for the recovery of soil organic carbon stock (7A; Ingram & Fernandes, 2001) and the humus storage capacity curve of some Estonian soils depending on the content of soil clay particles (7B; Astover and Lietuva, 2017).

In the case of Estonian agricultural soils, it should be taken into account that from the 1960s to the early 1990s, the main bedding in pig and chicken farming and large dairy and beef farms was bedding peat (slightly decomposed peat), which was transferred to the surrounding arable lands, but to a lesser extent also to cultivated grasslands. In total, according to the reports on the development of the domestic economy of the Estonian SSR, at least 24 million tons of bedding peat was transferred to agricultural lands as a soil improver (peat without additives) or as part of manure (relative peat humidity of 40%). This significantly increased the soil carbon content (Loide & Edesi, 2021) and considering the long-term decomposition rate of peat (Hyvonen et al., 1996; Karhu et al., 2012; Kauer & Astover, 2024), a significant part of it is still preserved in the soil. Arable land loses an average of 0.02 t/ha of organic carbon per year without the addition of organic fertilizer or soil improver, while organic carbon added with the root ball of plants (cabbage, cucumber, pumpkin, etc.) or as residual peat helps to mitigate the depletion of carbon stocks.

Composting

During the survey, composting the used peat substrate before reusing it in open field plant production was repeatedly mentioned, as it can have several positive effects. First, successful composting, which is accompanied by an increase in temperature inside the compost, reduces the risk of plant diseases, which is the main obstacle to the multiple use of peat substrates. Secondly, the substrate is enriched with nutrient-rich composted plant parts and used substrate is binding the nitrogen necessary for plant growth. Since leftover and discarded plants often go into the compost along with the substrate, the process is necessary to decompose the corresponding plant parts. If the substrate mixtures contain other main components in addition to peat (sand, wood fiber, perlite were mentioned during the survey), they also affect the final structure of the compost.

When used correctly, compost can also act as a plant protection product. Thanks to the compost, bacteria in the soil break down the development stages of fungal diseases more effectively. The aqueous extract of compost has similar properties: when sprayed with a solution made from the aqueous extract, microorganisms that inhibit pests are delivered to the plant. Good results have been obtained in the control of powdery mildew, rust diseases, stem, leaf and fruit rot (Albert, 2018).

However, the ready compost is mainly used in open-field beds, not in greenhouses and potted crops, because plant growers do not want to risk its uneven composition and quality. In the Netherlands, the risk of using compost when growing sensitive crops is assessed as very high, estimating the cost of growing peat to be approx. 1% of the cost of the final product, but the financial risk of direct damage in the event of failure to be 10-50 times more expensive (Schmilewski, 2008). If there is not much compost, in some gardens it does not end up in their production, but is distributed, for example, to local residents or their employees; in their use it still ends up in the open-field beds. When composting, it must be taken into account that CO_2 and, to a lesser extent, CH_4 are inevitably released during the process, but the amount of volatile carbon dioxide depends primarily on the composting temperature and the proportion of plant residue (roots, green mass). With a higher proportion of green mass, the annual carbon loss during composting can reach 18-22% of the initial carbon content (Komilis & Ham, 2006, Murayama et al., 2012, Blok et al., 2024).

Use in landscaping

While used peat substrate is not recommended for use in professional plant production or for transfer to natural soil with seedlings due to the potential spread of plant diseases or plant protection products and fertilizers, in artificial environments, such as cities and quarries being reclamated, residues from additives may even promote the development of vegetation. Some companies are also engaged in landscaping in addition to plant production and can direct substrate residues to urban landscaping when they arise.

The use of used peat substrates for quarry reclamation was not revealed in databases, survey results, or other sources. However, based on the collected data, it can be argued that used peat substrate is also too valuable for this purpose and its use for growing agricultural and horticultural crops is preferred. Secondly, there is enough used substrate left in Estonia and in different places to make its collection and use in large-scale landscaping worthwhile. When using a growing medium in landscaping, the proportion of peat carbon retained in the soil can be expected to be similar to that of agricultural soils or even higher, since the mineral soil used in landscaping usually has a lower organic carbon content than agricultural soils and is below the natural equilibrium state.

Adding to agricultural soils as a soil improver

A large part of the horticultural peat used in Estonia moves with the seedlings to the end consumer and is generally planted with the plant in open ground beds: in gardens, orchards, fields and artificial environments. According to a survey conducted among plant growers as part of this study, the majority of the peat substrate used and then separated from the plants also moves to the fields, where it remains as a soil improver to support plant growth, regulate the moisture regime and also replenish the carbon reserves of the soils.

One way to increase the organic matter or organic carbon reserves of the soil is to introduce organic fertilizers into the soil, including peat, which is a carbon-rich material. Peat, which is extracted as a natural resource, differs from common organic fertilizers (manure, compost) and agricultural plants in its composition (e.g. lower pH and nutrient content, wider carbon-nitrogen ratio): since the highly degradable compounds have already decomposed during the peat formation process, the decomposition rate of peat is significantly lower than that of other organic additives, and nearly 30% of the original peat carbon can be preserved in agricultural soil over a 100-year period (Kauer and Astover, 2024).

In a long-term experiment conducted in Ultuna, central Sweden (average annual temperature 5.4°C, annual precipitation 570 mm), which began in 1956, the retention of carbon in the soil (originally 36.5% clay, 41% silt, 22.5% sand) of peat added to fields was investigated, among other things. The following crops were grown in the experimental fields in succession: barley, oats, beet and rapeseed. By adding *Sphagnum* peat (pH 5.9; 800 g m^{-2} yr^{-1}) and mineral nitrogen (8 g m^{-2} yr^{-1} $Ca(NO_3)_2$) to the mineral arable soil every spring for 35 years (1956-1991), 69% of the carbon added with the peat remained at the end of the period (Hyvönen et al 1996). For all other added organic additives (manure, hay, sawdust, sewage sludge), significantly less of the carbon originally added remained, generally less than 30%. Based on the carbon added to the soil and the measurement results obtained, Karhu et al. (2012) also modeled the retention of peat carbon added to the soil at a certain point in time based on the same experimental field. It was found that 97% of the carbon originally added to the soil with peat had been retained after one year, 77% after 10 years, 62% after 20 years, 50% after 30 years and 14% after 100 years.

Use as raw material for alternative products

If the unused peat substrate is no longer suitable for horticultural use, its use as raw material for alternative products can be considered, where the changed properties of the substrate do not reduce the value of the used substrate as a raw material. For example, the University of Tartu is investigating whether peat would be suitable for the production of raw supercapacitors in the future as part of the project "Development of express analysis methods for micro-mesoporous materials for testing carbon supercapacitors synthesized from Estonian peat" (ETIS, 2023). Another potential end product could be the production of long-term carbon-storing biochar from used peat substrates. Since peat is a good thermal insulator due to its high porosity, it also has the potential to become a raw material for insulation materials on a larger scale as a natural recycable material. In all cases, the prerequisite for using used peat substrate as an industrial raw material is its collection from plant growers in very large volumes and with relatively uniform quality. The prerequisite for obtaining pure material is also washing out all unwanted additives from the used peat substrate. Peats differ somewhat in their properties and composition (Orru & Orru, 2003), but if residues of plant protection products and/or fertilizers have been used in them, as is typical of substrates, the cost of solvent used to clean the raw material is likely to be higher than that used to process natural peat.

The global market for activated carbon is growing rapidly. It is used in both granular and powder form in various devices, e.g. in the purification of gases, air and water. The global market exceeds 1.5 million tonnes and the European market is around 300,000 tonnes. In recent years, the market has grown by around five percent per year. Imports cover more than 70% of Europe's activated carbon use. Most of the activated carbon is imported from Asia and North America. In early 2023, the Finnish activated carbon producer Novactor opened the first Nordic activated carbon plant in Ilomantsi, which uses peat and wood as raw materials and has a production line capacity of around 5,000 tonnes. There are also plans to soon build a secaond activated carbon plant to Finland. Novactor's Finnish-produced activated carbon products have so far been well received by the industry, as the corona period has highlighted the uncertainty of long-distance imports in exceptional situations. In addition, activated carbon produced closer to consumers in Central Europe has a significantly smaller carbon footprint. Novactor's goal is to increase its market share to 10 percent of the world's activated carbon production in 10 years. (Neova Group, 2023) As a soil improver, activated carbon has also been seen as an opportunity for long-term storage of carbon in the soil and slow release for plant growth. However, it must be taken into account that thermal processing of peat raw materials – whether used or fresh peat – does not create additional carbon, but rather releases it, which is why such production is only reasonable if carbon capture equipment is integrated into the factory. The energy consumption of activated carbon production is also high.

When producing biochar using the torrefaction process, 40-70% of the original carbon content remains, and the resulting biochar is very stable in the long term. During pyrolysis, due to the higher temperature, only 10-50% of the original carbon content of the thermally treated substrate remains (Blok et al., 2024), but the method is suitable also if the substrate is contaminated with pathogens. Moreover, in addition to the produced biochar, carbon-rich oil and dry distillation gas are also obtained (the carbon content of them in the liquid and gaseous phases is not included in 10-50% of the original input).

Used substrate that has become waste

Although almost all used peat substrate is recycled, mainly in open-air beds and fields, a very small amount of it can also become waste. First of all, pots with substrate sold in retail stores together with salad and herb plants can end up as waste. While a very small amount (0.2%) remains not sold in stores and is thrown away as biodegradable waste, after the product is consumed, salad or herb substrate in households can end up in mixed household waste. Considering that about 1/3 of such substrate ends up in unsorted household waste, its amount would be approximately 230 m^3 of peat. Used substrate sorted into biowaste is generally composted and then also used in landscaping, both in households and industrially at waste stations.

Secondly, substrates discarded with wilted houseplants can become waste, which, depending on people's awareness, can also end up in both bio- and mixed household waste or can also be composted in households. Since the replacement of the substrate for houseplants is irregular and its volume cannot be reliably distinguished from the substrate used in greenhouses, it can generally be considered composted material. However, it is important to emphasize that a distinction must be made between compost prepared and used in gardens and household compost. In the latter case, it also includes collected food waste, which should not end up in plant production (especially food production), but can be used in landscaping in certain cases.

Hydrothermal treatment can be used for this type of waste, during that 10-20% of the original carbon is volatilized (Blok et al, 2024).

If the used growing medium contains a significant amount of fresh plant material (roots, aboveground biomass) and fertilizer residues, it can be used in a biogas reactor together with green mass, manure or slurry. The resulting digestate becomes more suitable for use as a fertilizer on agricultural soils in terms of the C, N and P ratio, since the difficult-to-decompose peat substrate remains largely undecomposed. Consequently, the growing medium is not a preferred component on its own or in systems optimized for biogas production, reducing gas productivity per unit mass (Lee & Heekwon, 2023). However, it can be considered as a waste management method and for ensuring that organic carbon partially reaches the soil in the form of digestate and that greenhouse gases are captured in the biogas plant.

Estimated volumes of the after-use of used peat substrates

The assumption for calculating the volumes of after-use is that the volume of horticultural peat used in Estonia in the same (203 thousand m^3) as for primary use in the same year (2022). The distribution by primary use has been previously presented in this study. Based on this, it has been estimated (Figure 8) based on the survey and other relevant available data that

1. horticultural peat used for growing forest seedlings completely ends up in the forest soil together with forest plants;
2. horticultural peat used for growing both young vegetable plants and greenhouse vegetables completely ends up in the field soil;
3. peat used for growing summer and perennial flowers mostly ends up in the soil together with the seedlings in gardens, orchards and landscaping; approximately 5% is estimated to be composted (unsold and waste plants; wilted plants);
4. horticultural peat used for growing fruit and ornamental trees and shrubs is completely planted in the soil in gardens, orchards and landscaping;
5. The vast majority (approx. 85%) of the peat substrate for herbs and salads goes into compost after use, the rest can also end up in mixed household waste through retail consumers and from there into incineration or landfill;
6. horticultural peat used in botanical gardens goes entirely into landscaping;
7. Cut flowers are grown in very small quantities in peat in Estonia today; the remaining substrate goes entirely into compost;
8. It is estimated that at least 19 thousand m^3 of horticultural peat is used in landscaping and shaping garden beds; this amount can entirely be counted as input to garden soils and landscaping;
9. The estimated amount of peat substrates sold in retail trade and corrected with the EAN conversion coefficient is at least 9800 m^3; this amount can be entirely counted as an input to garden and horticultural soil and landscaping;
10. Concerning a large part of the horticultural peat produced in Estonia and is not exported (~42.6% of domestic use), it is not possible to say what it is used for based on plant production and retail data. Considering the magnitude of the remaining peat use, it can be estimated that ~80% of it goes to garden and horticultural soils and landscaping, ~10% to agricultural soil with vegetable plants, and ~10% to compost after the initial use as a substrate, from where it also ends up in open-field beds after composting.

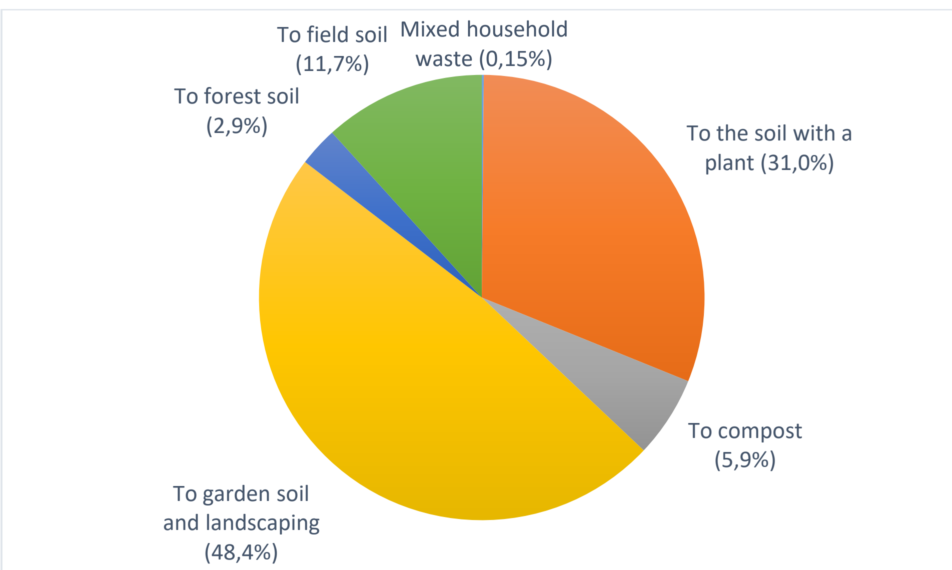


Figure 8. Estimated distribution of horticultural peat produced and used in Estonia by its after-use in 2022 (m^3).

International statistics on the subsequent use of used horticultural peat are available for very few countries (Kitir et al., 2018), but the general rule is that a proportionally larger amount of growing media from Estonia goes into agricultural soil (directly or after composting) in the Mediterranean countries and China, where the growing media is used more for vegetable growing (over 55%), whereas in the western European countries (Netherlands, Germany) peat is used more for growing ornamental plants and tree seedlings, but also for re-export with soil balls and soil. In Germany and the Netherlands, the cultivation of houseplants is also very important, and in this case, at the end of their life, it is common to collect and compost plants during waste management together with the soil balls and to use the compost for landscaping. Great Britain and Ireland clearly stand out from the others in terms of the large use of peat substrate in mushroom cultivation, from where residual peat generally ends up in agricultural soil after composting. In 2022, the share of private and professional peat use in the UK (totalling 950,000 m^3, of which private consumption was 470,000 m^3) was almost equal, and use is mainly influenced by the legislative enforcement of restrictions on the use of growing peat during the transition period. In professional horticulture, 32% of growing peat was used for growing container plants (280,000 m^3), 30% for mushroom cultivation (260,000 m^3), 16% for growing bedding plants in ornamental horticulture (143,000 m^3) and the remaining 22% is used for other potted plants, vegetable seedlings, greenhouse lettuce and bulb flowers (Kitir, 2018; Defra 2022). A similar distribution by use is also found in Ireland (Rialtas..., 2019).

Life Cycle Analysis (LCA) of peat substrates and their alternatives

Life Cycle Analysis (LCA) is a methodology through the environmental impacts of a product, service or activity are assessed throughout its entire life cycle – from the extraction of raw materials to use and finally disposal or recycling. The life cycle of the product can be either cradle to gate, cradle to end of life or cradle to grave, the latter method being the most complete in terms of calculating impacts. In the case of growing substrates, the cradle to end of life method is the most common (Vinci and Rapa, 2019; Stichnothe, 2022; Paoli et al., 2022) as information about the after-use is mostly lacking.

However, this leads to a significant overestimation of the climate impact, because the entire carbon stock of residual peat is calculated to be immediately oxidized with the end of the product's life, similar to the LULUCF and Growing Media approaches (Paoli, 2022; Quantis Switzerland, 2012), but from the perspective of the carbon cycle, not all organic carbon in the residual substrate is oxidized, but remains as a soil structure improver, moisture regulator and nutrient reserve to support soil biota and plant growth.

Life cycle analysis depends somewhat on both the length of the product cycle and the area of use of the substrate (the growing substrate is somewhat different for growing different crops), but the results of different studies reach fairly similar conclusions in the cradle-to-end calculation in terms of both the size of the environmental footprint and the comparison of peat-based growing substrate and its various alternatives.

In a comparison of growing substrates used in hydroponics, Vinci and Rapa (2019) highlight that perlite, rock wool and vermiculite have the largest environmental footprints in order of impact size (Figure 9). The most environmentally friendly are tree bark and sand, but at the same time the carbon footprint of tree bark was estimated to be one of the highest (1.1197 kg CO_2 eq for bark compared to 0.0121 kg CO_2 eq for sand).

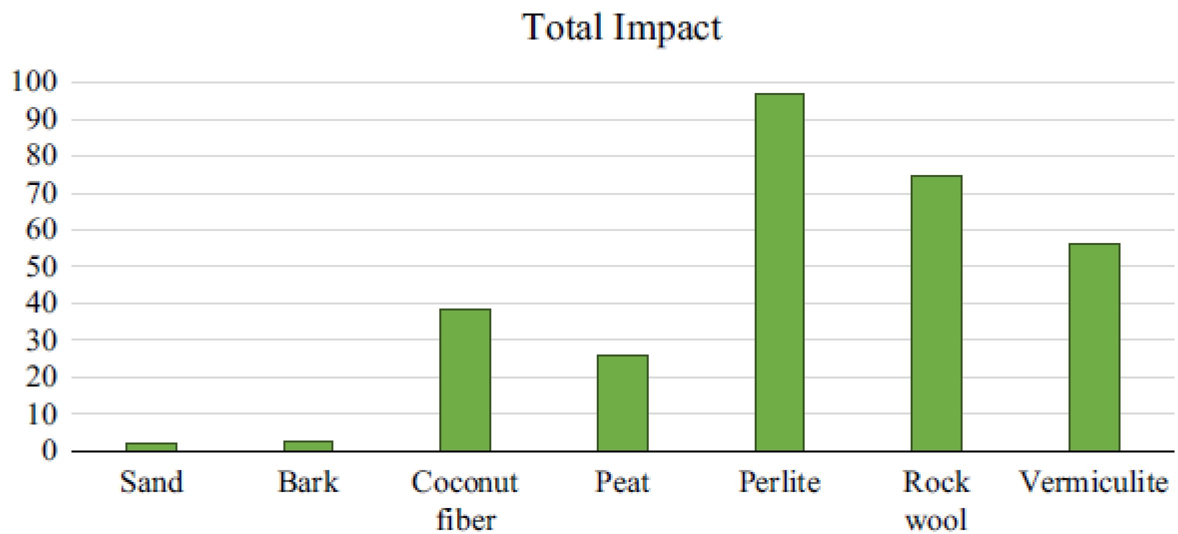


Figure 9. Summary of the life cycle assessment of different substrates used in hydroponics. Source: Vinci and Rapa, 2019.

According to the calculation of the life cycle cost (LCC), the authors find that the most expensive are peat, rock wool and bark, and the cheapest are sand, coconut fiber and perlite.

The results expressed in ecological score (i.e. Pt) of a study based on information on Latvian peat production show that the stage with the most significant impact on human health (2.3 mPt), climate change (1.39 mPt) and resources (1.48 mPt) is related to the transport of the final product, which in turn is related to the use of diesel fuel. In case of the ecosystem indicator, the largest impact is in peat extraction (1.59 mPt) and the opening of peat extraction sites. Similar to other substrates, the major impact from peat production results from the transport of the final product - substrate. Although Paoli et al. (2022) and other previously cited analyses have found that the logistics of growing media have a significant footprint over the entire product life cycle, this is still tens of times smaller than the footprint associated with the transport of final products, such as vegetables or ornamental plants. The environmental footprint of a grown product also varies greatly by latitude due to the different needs for heating energy and electricity for lighting. One of the reasons for using growing substrates is to enable local food and plant production, which reduces the overall logistics volume and thus the environmental impact.

In comparison with other alternative substrates used in gardening, it has been concluded that coconut fiber (48.51 mPt) has the greatest impact across various indicators, followed by rock wool (10.6 mPt) and peat (6.79 mPt). The most unfavorable in terms of climate impact is coconut fiber (47 kg CO_2eq compared to 32.1 for rock wool and 20.2 kg CO_2eq for peat). Stichnothe (2022) also finds in his study that the LCA climate footprint of light peat substrate is 26 kg CO_2eq, while the climate footprint of black peat substrate reaches 51 kg CO_2eq per cubic meter of substrate.

The most extensive study with the most substrate combinations was prepared by Quantis Switzerland (2012). Their results show that it is not possible to clearly identify any growing substrate as having the least or the most impact across all indicators. This applies to all areas of use: (1) fruits and vegetables, (2) potted plants, (3) pre-growing young plants and (5) the hobby market. However, for the (4) use categories, i.e. nursery plants, mixture 4.2 (50% light peat, 30% bark, 20% wood fibre) had the lowest impact on all indicators presented in the respective study compared to the other alternatives.

The following general trends can be observed for all growing media:

- growing media with a relatively high proportion of peat have a greater impact on climate change;
- growing media containing a large amount of green compost have a greater impact on human health;
- growing media containing a large proportion of coconut fibre have the greatest impact on ecosystem quality.

For functionally equivalent growing media components, it was observed that:

- coconut fiber has the greatest impact on ecosystem quality;
- mineral wool has the greatest impact on human health;
- peat has the greatest relative impact on climate change and resources.

The LCA environmental profile of peat in the Quantis Switzerland (2012) study is characterised by three dominant processes, depending on the impact categories considered: transport to the end user, end of life and peat extraction. Black peat generally has a higher impact than light peat, primarily due to its higher density. Peat transport affects almost all LCA indicators (30–80%), but in particular human health, water acidification and water eutrophication indicators, as fine particles arise during transport and NOx emissions are generated.

The end of life cycle, i.e. peat decomposition (in the calculation so-called instant oxidation), accounts for around 50% of the climate change potential. In contrast, peat extraction accounts for up to 60% of the impact on the resource indicator due to peat decomposition and on-site emissions. The extraction stage also accounts for more than 30% of the ecosystem quality impact, as land use changes due to extraction and it is estimated to last for 50 years. Less important than the latter three is the area related to substrate production (combined score 10-25%).

Figure 10 provides a summarized assessment of the climate impact.

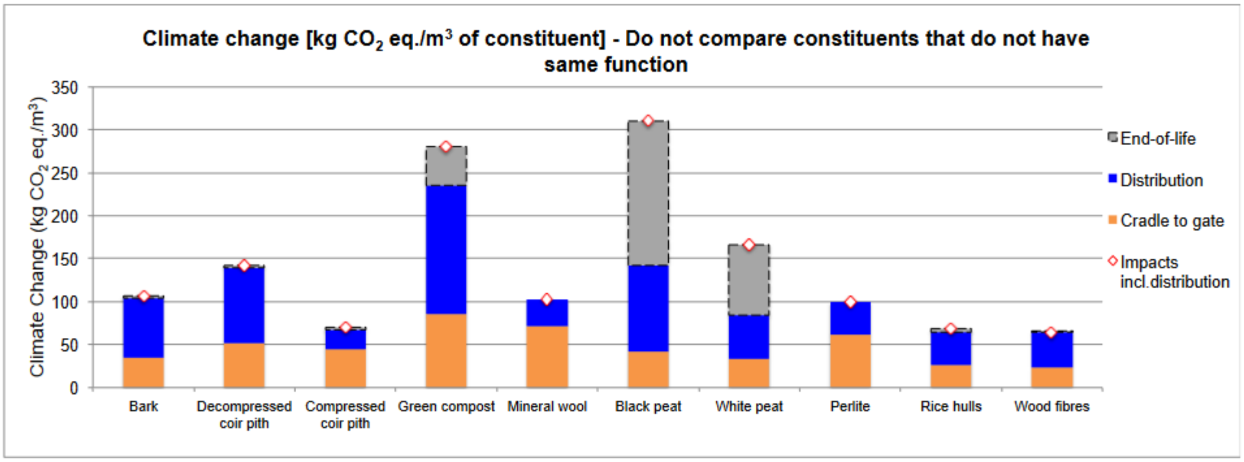


Figure 10. Comparison of different growing media and additives based on the LCA climate impact indicator using both cradle to gate and cradle to end-of-life methods. It is important to pay attention to the role of the end-of-life carbon flow, as this study assumes that all peat carbon oxidizes immediately and completely at the end of use. Source: Quantis Switzerland (2012).

Consequently, most LCA analyses of growing media have used the cradle to end of life approach, which does not take into account the subsequent use of residual peat, i.e. the transfer of most of the carbon to soils. This approach is primarily due to the LULUCF Tier 1 methodology and previously insufficient source data about the after-use. However, this has overestimated the carbon emissions in growing media from the perspective of the climate impact indicator and shown them to be completely oxidized during the substrate use phase. This could be considered a reasonable scope even if the substrate is incinerated as waste after use. However, since the material is mostly added to the soil (composted or without) and its use has an economic effect both as a soil improver and in terms of increasing yield (and ecosystem carbon stock), a cradle to grave approach is more justified. Based also on the results of this study, it is recommended to reassess the basis for compiling LCA of substrates based on the knowledge gained in recent years (Paoli et al., 2022; He and Roulet, 2023; Sharma et al., 2024).

Carbon flux during substrate use

Peat decomposition is a very slow process, controlled by weather/indoor climate and microbiological processes (mainly fungi, bacteria and archaea). The decomposition of the substrate is also affected by soil reaction (pH) and nutrient content (especially nitrogen compounds).

To determine the carbon emissions of horticultural peat and peat-based substrates over their life cycle, the qualitative change in their carbon compounds (change in the proportion of more easily and more difficultly decomposable carbon compounds during the life cycle) is assessed in the laboratory with a FTIR analyzer, the proportion of emitted/bound greenhouse gases (carbon dioxide CO_2 and methane CH_4) is determined; further, the temporal change in the organic carbon (Corg) content and stock in peat or peat-based growing media is determined. Since the use of growing media in plant production results in the production of both aboveground and belowground biomass during photosynthesis, the amount of carbon added to the substrate in the form of roots and root exudates during the plant growth period is also determined to compile the carbon balance.

Methods of carbon flux measurements

At the beginning of the experiment, the air-dry growing media was homogenized by mechanical mixing to ensure a uniform substrate bulk density and composition for the experiments. The growth containers used in the experiment were then filled with the substrate so that the weight of all containers of the same size was equal (a scale with an accuracy class of 0.1 g was used). From the filled growth containers, 15 random containers were selected for each substrate and container size using a random sampling method and sent to the laboratory to assess the initial carbon content and qualitative state of the substrate.

In the case of forest plants, complex samples of the substrate were taken to describe the initial state from both the bare-root seedling growing bed (5 complex samples, each consisting of ten subsamples) and from the pine plant growth containers with prepared substrate immediately before sowing the seeds.

Ornamental plants were purchased from garden centers and it was not possible to assess the substrate condition before planting. In their case, the initial sample was taken from the soil during the day after the plants were purchased, so that both fine and coarse roots were separated and only the root-free substrate was used for soil analysis.

Changes in the carbon balance during the plant growth cycle (soil respiration Rs, ecosystem respiration Re (=soil respiration + plant respiration), net gas exchange of the plant-soil system NEE (Net Ecosystem Exchange)) are periodically measured with portable gas analyzers LI-COR LI-7810 $CH_4/CO_2/H_2O$ and additionally N_2O/H_2O using LI-7820. The LI-7810 portable gas analyzer is suitable for gas flux measurement using the dynamic chamber method, its measurement frequency is 4 Hz and the accuracy class is 0.60 ppb at 2 ppm with 1 second averaging and 0.25 ppb at 2 ppm with 5 second averaging. The LI-7820 analyzer allows dynamic chamber measurements with the accuracy class of 0.40 ppb at 330 ppb with 1 second averaging and 0.20 ppb at 330 ppb with 5 second averaging.

The peat decomposition rate was determined based on the total loss of CO_2-C and CH_4-C measured during soil respiration (Rs). The gas flow was measured at least once every 10 days, the measurement lasted all day, 5 minutes per container, using the dynamic chamber method, and the plant containers were selected in random order. Since the plants were grown in a controlled environment (temperature, humidity, photosynthesis lamps), the Rs gas flux has a monotonic course throughout the day and the measurement results can be upscaled to 24 h starting from the filling of the container with substrate. The carbon emission covering the entire growth cycle may contain a trend. Therefore, the total carbon balance was found by multiplying the average value of all measurement days of the growth period by the number of days of the growth period of the respective culture. The annual decomposition rate was calculated by dividing the number of days in the year by the number of days of the growth period and multiplying it by the average emission value of the days of the growth period.

The control calculation was made on the basis of the mass balance principle – the difference between the initial weight of the containers with absolutely dry substrate and the final weight of the residue of absolutely dry growth substrate at the end of the growth period, where in the case of the initial and final weights of the substrate, the change in carbon content during the growth period was found based on the laboratory-determined C content.

To measure ecosystem and soil respiration gas flux, the LI-COR soil gas flux survey system Smart Chamber and dynamic air-circulating dark chambers of various sizes (diameters ranging from 10-50 cm, heights ranging from 25-50 cm with possible modular elevations in 70 cm increments) are used. The choice of chamber depends on the dimensions of the measured crop/plant according to the stage of plant development (Figure 11).

Figure 11. Gas flux measurement chambers for measuring soil respiration and ecosystem respiration (Re; left photo), and photosynthesis and net ecosystem gas exchange (Net Ecosystem Exchange NEE) (middle and right photos).

High-transparency dynamic transparent chambers were used for measuring NEE (including photosynthetic uptake) (Figure 11). The measurement system was equipped with an Apogee AT-100 PAR sensor, Stevens Hydraprobe and Decagon humidity and temperature sensors.

A Bruker FTIR analyzer was used to analyze changes in the qualitative properties of peat, which determined the initial spectra of the peat substrates (3 replicates were determined from each subsample, were averaged, and then the combined spectrum of each substrate was averaged), against it changes during the substrate use cycle were determined.

For the determination of organic carbon, the Elementar Analysensysteme GmbH Vario MAX Elementar analyzer and the elemental analyzer CHN vario MACRO cube were used to determine the organic carbon content separately in the solid phase (substrate) and in the water used for the extraction of underground biomass for the analysis of dissolved and undissolved organic C. Organic carbon was determined according to ISO 10694, inorganic carbon (as an additive to the substrate, pre-grown plants in agricultural/forest soil or agricultural soil to which previously used substrate has been added) according to ISO 10694.

Selection of plant cultures

The selection of plant cultures for analyses was based primarily on the fact that the areas with the greatest use of peat substrate would be represented: vegetable growing, ornamental gardening, forest tree seedling growing, and that crops with short, medium and long growth cycles would be represented.

Vegetables

Short-term growth cycle:

Lettuce Grand Rapids, Lollo Rosso, Red Salad Bowl (35-50 days) both as a container plant and as a 20-day pre-grown outdoor plant.

Medium-term growth cycle:

Icelandic lettuce Frillice, Regina dei Ghiacci (80-85 days) both as a container plant and as a 20-day pre-grown outdoor plant.

Long-term growth cycle:

Cauliflower Multi-Head F1, Alpha 6 – Fortados, Erfurt pre-grown as a container plant,

Kale Vert Demi-Nain pre-grown as a container plant,

Broccoli Atlantis F1, Calabrese Natalino pre-grown as a container plant.

For vegetables, one purely peat-based growing medium and one peat-based substrate with mineral additives was used. The plants were grown from granulated seeds. In total, a minimum of 50 plants for each lettuce and iceberg lettuce variety and >100 broccoli and cauliflower plants were grown in both years (2023 and 2024).

Ornamental plants

Short-term growth cycle:

hyacinth Aqua, Purple, Gipsy Princess

The plants were purchased as perennial bulbs in three stages of perennial growth and in 2024 for repeated experiments with bulbs that had not gone through a cold period and with a separate growing medium.

Medium-term growth cycle:

Spathiphyllum Chopin (1-year-old plants)

Long-term growth cycle:

Japanese azalea Anouk (1- and 3-year-old plants)

All plants of the same species have been purchased from one batch with peat-based growing medium. In the case of Japanese azalea, the surface of the peat substrate is covered with bark mulch. For the carbon content assessment of the substrate, the bark mulch was removed before soil analysis.

Forest plants

Bare-root seedlings

pine and birch (0- and 1-year-old seedlings, outdoors in beds with automatic watering and fertilization systems)

Container plants

pine (0-year-old sowing in a greenhouse under controlled conditions)

All plants are in the same completely peat-based substrate. The pots of container plants are lightly covered on the surface with perlite crumbs, but perlite is not added to or mixed with the substrate. For bulk density and chemical analysis, perlite is removed from the surface and only the substrate is counted.

Carbon flux: the examples of the most common plant culture groups grown on peat

Depending on the use, the conditions for decomposition of peat-based growing media vary greatly. The biggest difference in the change in carbon content in the substrate during the growth cycle results from whether the substrate is used outdoors (e.g. growing bare-root forest plants), indoors (ornamental plants in homes and offices or greenhouses), and how the soil moisture regime is controlled (maintaining a constant optimal regime or irregular threshold-based watering), fertilization, soil and air temperature, air humidity, the amount of photosynthetically active radiation and its daily distribution. The carbon flux of pre-grown plants and container plants is also affected by the construction of the pot or container that affects both water and air movement (Figure 12).

Figure 12. Containers used for growing vegetables and hyacinths.

Therefore, for horticultural peat produced in and exported from Estonia, it is necessary to use an average emission factor weighted by the volume of use and the share of the plant culture group. The primary basis for distinguishing groups must be the after-use of residual peat, and as further more data becomes available, these estimations can then be specified by plant culture groups.

Initial state of the growing substrate used for growing vegetables

Three growing substrates from two different manufacturers were used for growing vegetables, two of which did not contain any mineral filler, and in the case of the third substrate, peat was mixed with a mineral additive (Table 7). While all three peat-containing substrates are qualitatively similar, the effect of the mineral additive in substrate 1 is clearly evident at wavelength 1418.32 (Figure 13). Samples of the carbon content of the substrate were collected for laboratory analyses immediately before sowing the seeds.

Table 7. Initial organic carbon (TOC), inorganic carbon (TIC) and ash content of vegetable growing media in percentages based on absolute dry matter

Sample	Sample air-dry weight (g)	Dry (105°C) sample weight (g)	Dry matter content (%)	TOC (% C)	TIC % C	Ash content (1000°C) %
Substrate 1	7.69 (±0.70)	7.04 (±0.67)	91.5 (±0.57)	42.0 (±1.41)	<1	15.9 (±0.91)
Substrate 2	18.11 (±0.63)	16.53 (±0.64)	91.3 (±0.54)	47.8 (±0.50)	<1	5.8 (±0.07)
Substrate 3	9.17 (±0.80)	7.84 (±0.70)	85.5 (±0.28)	48.4 (±0.55)	<1	5.4 (±1.15)

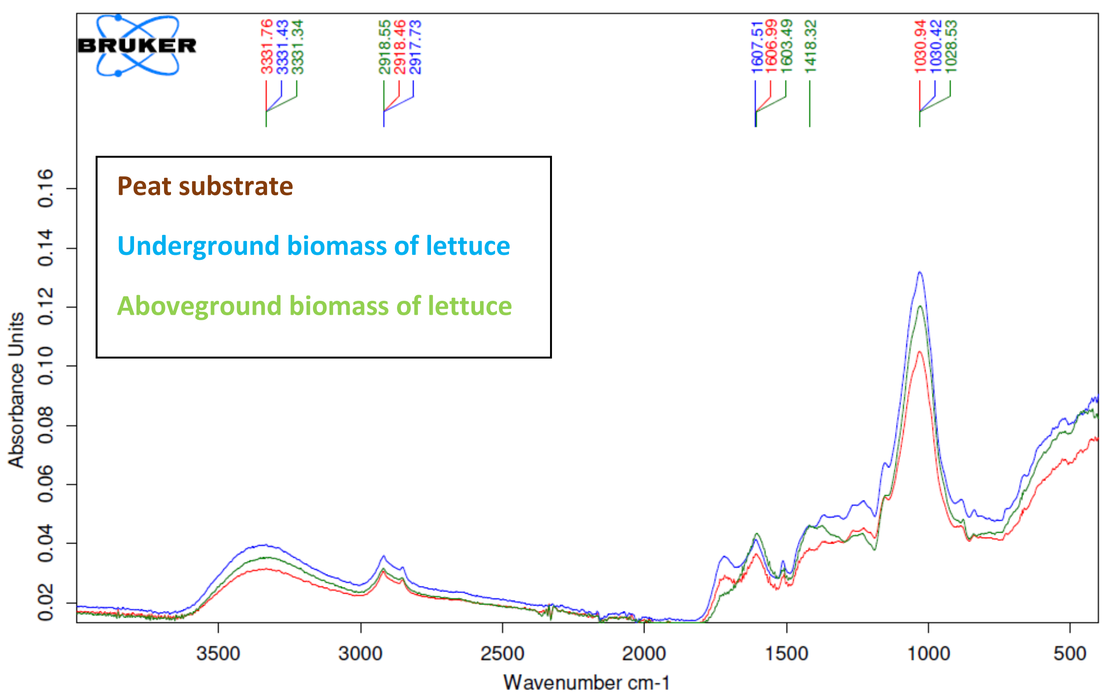


Figure 13. FTIR spectra qualitatively characterizing the initial state of peat-base substrates used for growing vegetables.

Vegetable substrate use and carbon fluxes

Vegetable growing is one of the most important users of peat-based growing media worldwide. In Europe, the largest consumers of growing media in vegetable growing are the Netherlands, where this sector accounts for nearly 30% of consumption (Verhagen et al., 2009), France and the Mediterranean countries, where the use of peat-based substrates in vegetable growing exceeds 40% (Kitir et al., 2018). It is estimated that over 82% of the peat exported from Estonia is used for growing vegetables (see Figure 5). In vegetable growing, peat is used both for greenhouse cultures (e.g. salads, herbs, etc.) and for pre-growing seedlings of plants grown outdoors (e.g. cauliflower, broccoli, etc.). Vegetables are grown in greenhouses on approximately 1.612 million hectares worldwide. Asia and China account for the largest share with 55%, Europe (Spain and Italy with the largest share) with 23%, followed by North and South America.

Lettuce

Lettuce (*Lactuca sativa* L.) is a plant culture with a short growing season and is widely grown worldwide. In most cases, lettuce is pre-grown in a small amount of peat and then grown under controlled conditions or planted outdoors. When grown in a bed, the planting spacing for leaf lettuce is 20x40 cm, or 120,000 plants per hectare. The planting spacing for iceberg lettuce is typically 40x40 cm, or 62,500 plants per hectare.

The growing season for lettuce is very short, usually 45-60 days for lettuce, and 45-85 days for iceberg lettuce. Due to the short growing season, changes in the growing medium are minimal and carbon loss as gaseous emissions is low, but since a very small amount of substrate is used to grow the plant, its recycling is difficult and most often the residual peat is composted together with the aboveground biomass added during the growing season (Table 8).

Table 8. Organic carbon (C %), total nitrogen and hydrogen content (%) of aboveground (leaf) and belowground (root) biomass of leaf lettuces and iceberg lettuce, and the carbon/nitrogen and carbon/hydrogen ratios determined from dry matter and the mass (g) of the aboveground and belowground parts as dry weight and the mass of carbon found in the biomass (g). The C/N ratio is one of the indicators of the decomposition rate, the C/H ratio indirectly characterizes the complexity of organic compounds through potential hydrogen bonds.

		C (%)	N (%)	H (%)	C/N suhe	C/H suhe	Mass (g)	C (g)
Grand Rapids	Leaf	42.3±0.57					4.3±0.6	1.8±0.27
	Root	44.5±0.61					0.6±0.20	0.3±0.09
Red Salad	Leaf	42.3±0.57	2.6	5.7	16.7	7.4	5.2±0.61	2.2±0.27
Bowl	Root	44.5±0.61	2.1	5.9	21.2	7.6	0.5±	0.2±
Regina dei	Leaf	42.1±0.56	1.9	5.8	22.9	7.3	4.2±0.56	1.8±0.23
Ghiacci	Root	45.0±0.49	1.3	6.0	34.8	7.5	1.0±0.19	0.5±0.08

Lettuce is predominantly grown hydroponically year-round, where air temperature (16-23°C), light and humidity are optimized for growth. The development of plant biomass (dry matter) growing under controlled conditions is depending on the optimality of conditions, is characterized by logistic growth models developed by Fraile-Robayo et al. (2017), which are based on the cumulative number of temperature days (e):

Parameter	Logistic model	R^2
Total dry mass cycle 1	$Y = \frac{36.764}{1 + e^{-0.1762*(ddt-44.563)}}$	0.99
Total dry mass cycle 2	$Y = \frac{26.223}{1 + e^{-0.1527*(ddt-35.148)}}$	0.99

where Y is plant biomass (dry matter in grams),

dat is the number of days after the plant has been planted.

Using the above-ground and below-ground biomass ratios and carbon content determined during this study (Table 8) in the Fraile-Robayo et al. (2017) formulas, it is possible to find the biomass of lettuce that can be realized (sold) at different ages and the biomass of roots that are subject to composting with the remaining peat substrate and the corresponding amount of carbon.

The greenhouse gas flux from the substrate of hydroponically grown lettuces showed that despite constant humidity, the root system and soil ball of plants grown in pots with air gaps have relatively good aeration and very weak methane oxidation (> -0.0001 CH_4-C mg C/g SOC) and less than 0.0001 N_2O-N (mg N/g SOC) emission occurred. The decomposition and volatilization of carbon in the peat substrate as CO_2 was 0.0032 g/m^2/day, or 14.7% of the carbon initially found in the growing substrate oxidized when upscaled to a year. In reality, the lettuce growing season is very short, and the average monthly carbon loss was 1.22%. Considering the maximum growing season of lettuce to be 60 days, 2.44% of the carbon found in the substrate oxidized as CO_2.

Based on the initial mass (3.79 ± 0.34 g) and carbon content (48.4 ± 0.55 %) of the growing substrate and the mass (3.35 ± 0.39 g) and carbon content (43.1 ± 0.62 %) at the end of the year-long growing cycles, the carbon loss was 11.6%, or 1.93% of the initial carbon stock oxidized as carbon dioxide per 60-day growing season.

The lower carbon loss measured by the mass balance method indicates that part of the organic matter generated during the growth period by microbial activity remains in the soil. According to the FTIR spectrum (Figure 14), the aboveground and belowground biomass are very different in terms of the qualitative properties of their organic matter. Belowground biomass is qualitatively close to the growth substrate but with a lower lignin and higher cellulose content.

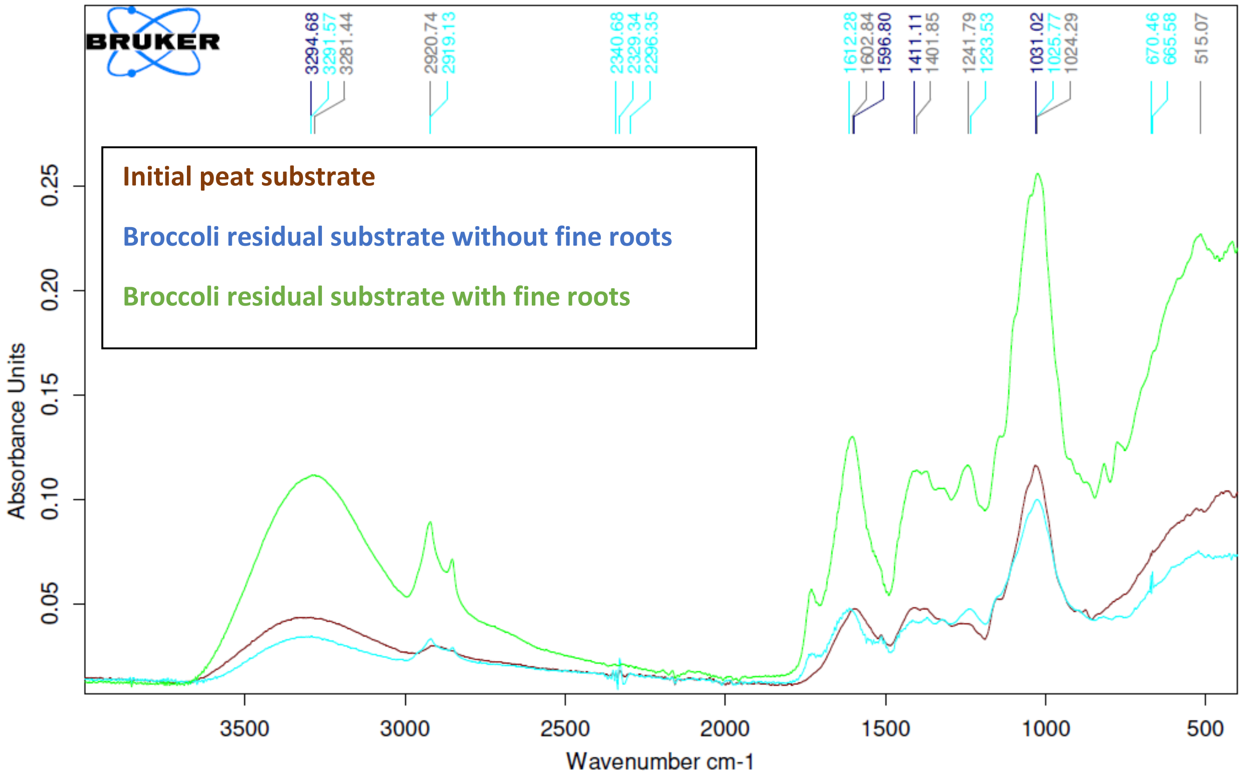


Figure 14. Qualitative difference between aboveground, belowground and growing medium of lettuce based on FTIR spectral analysis.

Cauliflower, kale and broccoli

According to their substrate use, these plant cultures form a similar group, where the substrate is important for pre-growing the young plant (on average 30 days) that are planted together with the substrate to the mineral soil at the growing site.

A typical planting pattern is 40 x 60 cm spacing, or approximately 40,000 plants per hectare. The amount of substrate used for pre-growing each plant is 16.5±0.64 grams of dry matter, or 7.89±0.26 grams of organic carbon at 47.8% organic carbon content.

From sowing to planting (at the 4-5 leaf stage), the seedling grows in a container for 25-30 days. During this period, the soil ball is evenly moist but aerated, which is why methane and nitrous oxide emissions were insignificant throughout the experiment (< 0.0001 g per 16.5 g container per year). 0.12 g C per container, or 1.5% of the original substrate carbon content, was oxidized as CO_2 over a month, which, when calculated to a year, would be 1.47 g CO_2-C.

The mass loss according to the mass balance method during pre-cultivation of cabbage, similar to lettuce, turned out to be smaller than calculated from the gas flux. Based on the mass balance calculation, the mass loss of organic carbon calculated to a year is 10.8 %, or 0.9% of organic carbon oxidized and leached during the 30-day pre-cultivation period.

From the perspective of the carbon cycle, it is important to keep in mind that when growing cabbages, organic carbon found in the substrate is transferred to the soil with the root ball, less than 25% of the aboveground biomass (commercial inflorescence) is removed from the field with the harvest, and 60-75% remains in the field as an input of organic matter, and the belowground biomass also increases the carbon content of the soil (Hu et al., 2011; Gavilanes-Terán et al., 2016, Granado-Castro et al., 2024). In the case of cauliflower, a similar estimated amount of aboveground biomass remains in the field (Petkowicz, 2020). In the case of kale, primarily the partially woody stem, lower leaves and underground part remain in the field. Table 9 provides an overview of the carbon content of different parts of the plant.

Table 9. Organic carbon (C %), total nitrogen and hydrogen content (%) and carbon/nitrogen and carbon/hydrogen ratios of aboveground herbaceous (herbaceous), woody (stem) and belowground (root) biomass of cauliflower, kale and broccoli as determined from dry matter and mass (g) of aboveground and belowground parts as dry weight and mass of carbon in biomass (g). The C/N ratio is one of the indicators of decomposition rate, the C/H ratio indirectly characterizes the complexity of organic compounds through potential hydrogen bonds

	C (%)	N (%)	H (%)	C/N ratio	C/H ratio	Mass (g)	C (g)
Cauliflower leaf	38	3.6	5.0	11	7.7	81.7	31.0
Cauliflower stem	42	3.5	5.7	12	7.4	38.0	16.0
Cauliflower root	45	2.7	5.7	17	7.9	16.4	7.4
Cabbage leaf	40	4.0	5.2	10	7.6	198.4	79.4
Cabbage stem	46	1.6	5.8	29	8.0	60.3	27.7
Cabbage root	35	2.0	4.5	17	7.8	32.5	11.4
Broccoli leaf	42	4.3	5.5	10	7.6	101	42.4
Broccoli inflorescence	44	6.5	6.3	6.8	7.0	22.1	9.7
Broccoli stem	42	3.0	5.4	14	7.8	56.6	23.8
Broccoli root	46	1.4	5.8	32	7.9	36.2	16.7

Since a considerable part of the plant biomass of cabbages remains in the growing site, the changes in organic carbon and nitrogen content of these plant parts and the residual substrate were analyzed (Table 10). Fresh underground biomass in the form of fine roots increases the carbon content, but due to leaching, the total nitrogen (N %) content decreases.

Table 10. Changes in the substrate organic C, total N and H (%) content of cauliflower and broccoli in arable soil after the growing; the aboveground herbaceous (leaves) biomass of broccoli was determined from dry matter

	C (%)	N (%)	H (%)	C/N ratio	C/H ratio
Cauliflower initial substrate	42	1.6	5.9	26	7.1
Cauliflower residual substrate with roots	44	0.95	5.3	46	8.2
Broccoli initial substrate	41	1.6	5.8	25	7.0
Broccoli residual substrate with roots	46	0.98	5.6	47	8.2
Broccoli leaves in autumn	42	4.3	5.5	10	7.6
Broccoli leaves after winter	42	3.1	5.7	14	7.4

During the growing season, cellulose-rich organic matter is added to fine-rooted residual peat and mineral soil, and the proportion of nitrogen compounds and hemicellulose decreases (Figure 15).

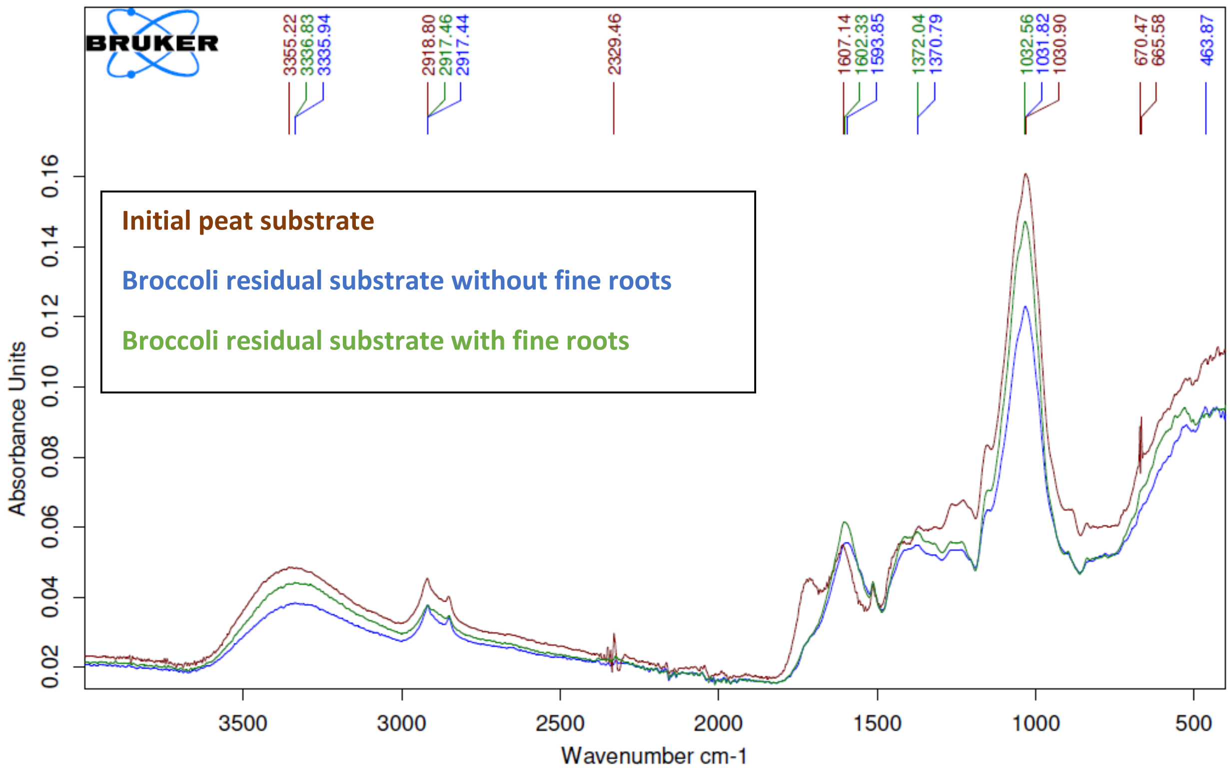


Figure 15. Qualitative difference between the initial substrate used for pre-cultivation and the residual substrate with and without fine roots after the growing season based on FTIR spectral analysis.

Considering that an average of 40,000 cabbage plants are grown on one hectare, after deducting the carbon dioxide and dissolved organic carbon that has been oxidized during the pre-cultivation of the seedlings, 7 grams of organic carbon are introduced into the field soil with each plant, or 40,000 plants x 7 g = 280,000 g = 0.28 tons of organic carbon. An average of 12 g is added with underground biomass, and 47 g with above-ground biomass for cauliflower and 66 g with broccoli. Thus, 2.36 t of organic carbon is added to the 0.28 t carbon of residual peat in a cauliflower field with plant residue, and 3.12 t of organic carbon in a broccoli field.

Substrate use for ornamental plants and carbon fluxes

Azalea

Azalea is an ornamental plant that has a relatively long lifespan, requiring an acidic growing medium for its cultivation, and therefore peat-based substrates are predominantly used. It is an ornamental plant widely grown across Europe that is used as a houseplant and office plant in cooler climates, and as an outdoor plant (or part of the year as an outdoor plant) in milder climates. As a specimen plant, azalea is characterized by a longer lifespan and the formation of a woody stem and branches, which makes the carbon cycle significantly different from bulbous flowers or ornamental herbaceous plants.

Although biologically it is a long-lived woody plant, azalea is still quite capricious in terms of its growing environment and as an ornamental plant after the plant is sold, its lifespan is usually not very long. In this study, typical consumer behavior was simulated by placing plants in offices and private homes with different orientations (and lighting conditions) in a large office building, under the care of different people. The average lifespan of 3-year-old plants was 8.6 months, nearly 29% of all plants died within 6 months (mainly due to irregular watering and bright sunlight during the holiday period), 50% lived for 6-12 months, and 21% of plants continued to live for more than 12 months.

The changes that occur during plant growth are characterized by Tables 11, 12 and the gaseous volatile part by Figure 16. Plant biomass has a higher carbon content than the peat substrate, so during the growing period, both aboveground and belowground biomass increase the carbon stock, which compensates for the carbon dioxide released from the substrate during the growing period. Both the substrate and young growths, as well as the leaves and flowers forming the litter, have a low C/N ratio, which creates favorable conditions for microbiological decomposition.

Table 11. Organic carbon, total nitrogen and hydrogen content (%) of the substrate, aboveground and belowground biomass of Azalea 'Anouk' (Azalea japonicum) C3 container plants, and the carbon/nitrogen and carbon/hydrogen ratios determined in a dry matter basis. The C/N ratio is one of the indicators of decomposition rate, while the C/H ratio indirectly characterizes the complexity of organic compounds through potential hydrogen bonds.

Azalea japonicum* "Anouk", *C3 container	**C (%)**	**N (%)**	**H (%)**	**C/N ratio**	**C/H ratio**
Substrate	46	1.3	5.1	35	8.9
Roots	52	0.93	5.7	56	9.1
Stem and woody branches	51	1.0	5.9	51	8.6
Growths, leaves, flowers	47	1.9	5.6	25	8.4

Table 12. Carbon stock and its annual change in Azalea 'Anouk' (Azalea japonicum) C3 container plants. Plant biomass and amount of growing medium are measured values. Annual root biomass increment is a calculated value based on the ratio of aboveground to belowground biomass and the assumption that this ratio is maintained in a 2-3 year old plant

	Aboveground biomass			Underground biomass		Annual biomass production	Substrate	Substrate and underground biomass
	1-year shoots, leaves, flowers	Woody biomass	Total above-ground biomass	1-year roots	Roots total	1 year underground + 1 year aboveground biomass		
Amount (g)	38.6±2.46	83.3±3.03	124.7±7.31	33.1±2.33	115.5±7.91	71.8±4.79	172.8±11.72	288.3±16.23
C (%)	47	51	50	52	52		46	48
C stock (g)	18.2±1.16	42.5±1.54	62.3±3.66	17.2±1.21	60.1±4.11	35.4±2.37	79.5±5.39	138.4±7.79

The substrate of azalea is well aerated and the decomposition of the substrate mainly produces CO_2. The emission of methane and nitrous oxide is statistically insignificant and it is rather a slightly methane-oxidizing environment. Gas flux measurements show (Figure 16) that azalea emits 0.27 mg CO_2-C g^{-1} SOC (1 g organic carbon in dry matter of the substrate) per hour. This corresponds to an annual carbon loss as CO_2-C of 2.33±1.27 grams or 1.76% for a C3 container.

Nielsen et al. (2023) experiments performed in the mesocosm confirm the results of this study that in open and well-aerated peat soil/growing medium, the main emitted gas is CO_2 (up to 99% of the greenhouse gas flux), while the contributions of methane and nitrous oxide are insignificant. However, the results of the Danish experiment show that it is critical to keep the peat pH below 6.5 and minimize the nutrient content (N and P) to limit the emission.

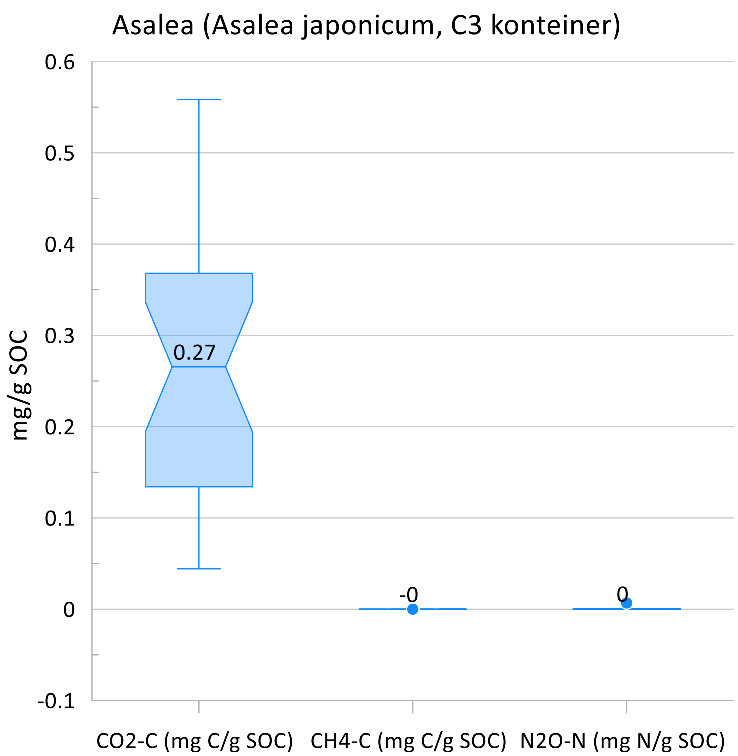


Figure 16. Greenhouse gas emissions from the growing medium of Azalea 'Anouk' (*Azalea japonicum*) C3 container plants (3 years old) in mg/g SOC.

Although the growing medium loses carbon (1.76% per year, or 2.33±1.27 g per plant container), 35.4±2.37 g of carbon is bound in the aboveground and belowground biomass. Unlike peat, plant biomass is an organic matter rich in easily degradable cellulose and hemicellulose, which decomposes almost three times faster when composted and added to mineral soil than peat added in the same volume (Niklas and Joergensen, 2001), but from the perspective of the carbon cycle, this must be considered as an additional amount of carbon bound from the atmosphere when using the substrate.

Hyacinth

Due to its good moisture retention capacity, peat-based substrate is the most preferred for bulbous flowers sold as a growing, time-varying plant. Hyacinth (*Hyacinthus*) is one of the most common bulbs sold as a plant, which was therefore the main crop of ornamental plants grown for planting in this study, but in addition, daffodils and tulips grown for planting were also compared in terms of the properties of the substrate.

The growth cycle of hyacinths (and other bulbs) used for planting is quite short: approx. 70 days of preparation in a cold room (approx. 0-8 °C) in moderately dry substrate and humid air (90%); then the beginning of the growing season in a moderately warm room at 15-20 °C with watering, and a few weeks to a month until the end of flowering, while the plant is growing herbaceous biomass. Since the nutrient reserve of planting bulbs is in the bulb, fertilization of planting bulbs is generally not necessary and therefore the chemical changes in the substrate are primarily related to microbiological decomposition processes occurring due to moisture and the organic matter released from the bulb and formed by the fine roots.

The study used 2 Dutch-origin plant batches purchased from Estonia that had undergone a cold period but were not yet in an active growing season, and hyacinth, daffodil and tulip bulbs from one Dutch-origin plant growing company that had not undergone a cold period, as well as the substrate of this company, which was purchased from Latvia. Laboratory analysis showed that the Dutch batch purchased from Latvia was identical to the substrate intended for hyacinth, tulip and daffodil. Therefore, all results related to the substrate are presented in Table 13, while those related to bulbs and biomass reflect only the results of hyacinth.

Table 13. Organic carbon, total nitrogen and hydrogen content (%) and carbon/nitrogen and carbon/hydrogen ratios of the substrate, aboveground and belowground biomass of hyacinth (*Hyacinthum orientalis*) P7 container plants, determined from dry matter. The C/N ratio is one indicator of the rate of decomposition, while the C/H ratio indirectly characterizes the complexity of organic compounds through potential hydrogen bonds.

Hyacinth, P7 container	C (%)	N (%)	H (%)	C/N suhe	C/H suhe
Substrate	49.5±1.81	1.4±0.39	5.2±0.17	39.0±4.82	9.4±0.54
Bulb	46.4±0.78	2.4±0.47	6.1±0.18	19.3±3.78	7.5±0.20
Aboveground biomass	45.1±0.46	1.9±0.61	6.1±0.00	26.0±9.54	7.4±0.06

Table 14. Carbon balance of hyacinth (*Hyacinthum orientalis*) P7 container plants from the beginning of the growing season to the end of the growing season (4 months).

	Start	End	Start	End	Start	End
	C (%)		**Dry matter mass, g**		**C_{org} stock, g**	
Substrate	49.5±1.81	47.8±0.68	25.3±3.15	21.2±3.02	12.52	12.09
Bulb	46.4±0.78	45.2±0.65	18.6±3.07	15.6±1.74	8.63	7.05
Aboveground biomass	0	45.1±0.46	0	3.0±0.91	0	1.35
Balance						**-0.66**

The main carbon stock loss occurs during the growing of timed hyacinth at the expense of flower bulb biomass (1.58 g). That is primarily due to the fact that larger and more viable bulbs (size 16/17) are preferably used for timed planting, but these cannot grow an equivalent replacement in a small (P7) container. **The carbon stock loss of the substrate, estimated by the balance method, is 3.4% per growing period** (4 months), which is quite high, but coincides with the carbon loss estimated as the measured CO_2-C flux. 0.08±0.06 mg CO_2-C per g^{-1} SOC is oxidized as carbon dioxide, or 0.71 g C is oxidized per P7 hyacinth container per year. The relatively high carbon loss can be explained by the fact that weakly decomposed peat is used as the substrate. That is also indicated by the FTIR spectral analysis result (Figure 17), which is similar to the spectrum of poorly decomposed bog peat. Changes occurring during the growing season (the original substrate is shown with darker lines, the substrate analyzed at the end of the growing season with lighter lines) have occurred uniformly across the entire spectrum, and the signature indicating fresh organic matter has rather been amplified at wavelengths 1032 and 1591.

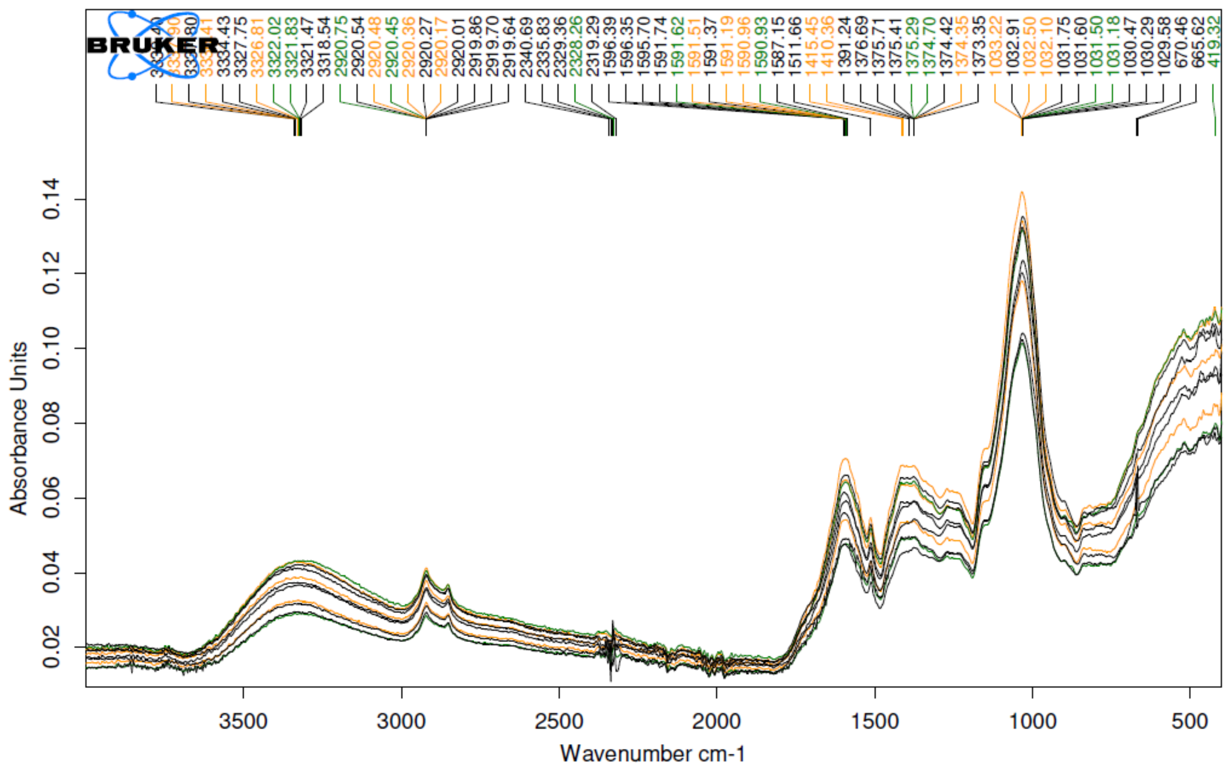


Figure 17. FTIR spectrum characterizing the qualitative change of the substrate, which shows that no significant changes have occurred during the growing season. Darker lines characterize the original substrate, lighter lines characterize a subsample of the same substrate after the end of the growing season.

Spathiphyllum

Spathiphyllum (*Spathiphyllum*) is a strong and widespread ornamental plant; its carbon reserve is stored in herbaceous biomass. The plant is tolerant of light conditions and tolerates semi-shaded growing sites well. Since the plant grows relatively quickly, it requires frequent repotting (every 1-2 years). Both the substrate and the plant biomass have a relatively low carbon content (table 15) but a high nutrient and water content (leaves 87.4%, roots 85.4%). Therefore, the plant biomass is suitable for composting at the end of the plant's life, but mineralization is rapid.

Table 15. Organic carbon, total nitrogen and hydrogen content (%) of the growth substrate, aboveground and belowground biomass of Spathiphyllum "Chopin" (*Spathiphyllum*) P8 container plants, and the carbon/nitrogen and carbon/hydrogen ratios determined from dry matter. The C/N ratio is one of the indicators of decomposition rate, while the C/H ratio indirectly characterizes the complexity of organic compounds through potential hydrogen bonds.

Spathiphyllum "Chopin", P8 container	C (%)	N (%)	H (%)	C/N suhe	C/H suhe
Substrate	43.8	1.2	4.7	36	9.3
Plant biomass	43.5±0.53				

The carbon stock in the plant biomass of Spathiphyllum exceeds the amount of carbon in substrate (Table 16). The carbon in the plant biomass is stored primarily in the aboveground part and carbon sequestration based on the mass balance is rapid: an average of 14.3 g C per year, which is why the lush plant also requires frequent replanting.

Table 16. Carbon stock in the soil and plant biomass of Spathiphyllum "Chopin" (Spathiphyllum), P8 container plants

	C_{org}, %	Dray matter, g	C_{org} stock, g
Substrate	43.8	44.8±3.66	19.6
Aboveground biomass	43.5±0.53	44.7±7.62	19.4
Root	43.5±0.53	16.6±6.38	7.4
Total plant biomass	43.5±0.53	61.7±10.1	26.8

Due to good aeration of the substrate and the rapid nutrient consumption resulting from the rapid growth, growing Spathiphyllum does not emit nitrous oxide or methane. On average, 0.03 mg C g^{-1} per SOC is emitted as carbon dioxide, or per P8 pot, the growing substrate loses 0.25 g C per year (or an annual carbon loss of 1.29%). The amount of carbon added as biomass (aboveground + belowground) is 14.3 g C per year.

Forest tree seedlings

Studies of forest tree seedlings and substrate were conducted in the nursery of Eesti Metsameistri Taimekasvatus OÜ in the village of Suure-Rakke, Tartu County (Figure 18). The nursery uses an automated irrigation and fertilization system and grows plants in outdoor fields on a 20 cm layer of substrate. From 2023 it will also grow container plants in a greenhouse (pine seedlings, estimated at 2 million plants per year).

Figure 18. The research area of forest tree seedlings at the nursery of Eesti Metsameistri Taimekasvatus OÜ: the greenhouse for growing container plants (left), the interior of the greenhouse for growing container plants (middle), and the measurement of ecosystem respiration in a bed of open-rooted annual pine seedlings (right).

The same peat-based growing medium is used for both outdoor and container plant cultivation. During the growing season, the seedlings are fertilized with NPK (30:10:10) fertilizer, and in the second half of the summer with PK and K fertilizer. The substrate was prepared for sowing in mid-April 2023, and the seeds were sown from the last week of April to the third week of May. A sample of the initial substrate and the substrate of 1-year-old seedlings (roots were removed from the substrate with 1-year-old seedlings) were collected immediately after substrate preparation and before sowing the seeds. Since the initial substrate has been supplied by the same manufacturer for at least last 3 years and in 2023 it was used for growing container plants of pine, open-rooted black alder, common ash and pine seedlings, the initial substrate presented in Table 8 is comparable both by species and for assessing changes in the substrate in the previous year's seedlings.

In addition, the Tartu Rõõmu tee nursery of the Estonian Forest Management Centre (RMK) was also used for this study for measuring container plants (spruce and pine). The RMK nursery used similar technology, identical substrate and the same growth containers as Eesti Metsameistri Taimekasvatus OÜ. The parallel use of several large nurseries ensures greater representativeness of the results.

Since deciduous and coniferous trees secrete different root exudates and their litter has different acidity, we can assume different decomposition rates of peat. The results confirm this: if the C_{org} content of the initial substrate was 48.0±0.68%, then there was no significant change in the case of birch seedlings within one year (C_{org} content 47.7±1.46%). In the case of pine seedlings, the variability of the carbon content is similar to the birch seedlings, but the carbon content is lower (46.0±1.43%).

Table 17. Initial organic carbon (C_{org}, %) and inorganic carbon (TIC) content of forest plant growth substrates in percentages based on absolute dry matter.

	Air-dry sample mass (g)	**Dry (105°C) sample mass(g)**	**Dry matter content (%)**	**C_{org}, %**	**TIC % C**
Initial substrate	52.5 (±4.16)	11.6 (±1.25)	22.0 (±0.81)	48.0 (±0.68)	<1
1-year birch	31.8 (±5.90)	11.2 (±1.08)	35.6 (±4.53)	47.7 (±1.46)	<1
1-year pine	57.1 (±5.42)	12.1 (±0.56)	21.3 (±2.20)	46.0 (±1.43)	<1

Although the same substrate is used for bare-rooted and container plants, as well as for plants grown in a container-field system, concerning the carbon cycle it is important to distinguish between seedlings grown as bare-rooted and container plants. Over 90% of the substrate used for growing bare-rooted plants remains in the nursery and is reused there, as a soil improver in the fields for further growing of trees, as a soil improver in other fields or used for other purposes, but in the case of container plants, the peat ball around the seedling roots goes into the forest soil (Figure 19). Therefore, it is necessary to know exactly the mass and carbon content of both the container plant (Table 18) and of the peat ball around its roots (Table 19).

Table 18. Organic carbon, total nitrogen and hydrogen content (%) of aboveground and belowground biomass of forest plants grown as container plants, and the carbon/nitrogen and carbon/hydrogen ratios determined from dry matter. The C/N ratio is one of the indicators of decomposition rate, while the C/H ratio indirectly characterizes the complexity of organic compounds through potential hydrogen bonds.

	C (%)	**N (%)**	**H (%)**	**C/N suhe**	**C/H suhe**
Pine, aboveground	47.9±1.0	1.5±0.2	6.7±0.1	32±3.3	7.1±0.2
Pine, root	48.1±1.3	1.1±0.2	6.4±0.1	44.2±7.3	7.5±0.3
Pine, substrate	40.7±2.5	0.9±0.0	6.1±0.1	47.5±0.4	6.6±0.2
Spruce, aboveground	47.0±1.0	1.1±0.2	6.6±0.1	43.3±6.6	7.1±0.2
Spruce, root	47.7±0.5	1.0±0.2	6.2±0.1	48.8±8.7	7.7±0.1
Spruce, substrate	41.0±1.4	0.9±0.1	6.1±0.1	45.8±3.8	6.7±0.1
Substrate (without plant; control)	37.3±1.2	0.8±0.0	6.1±0.0	45.4±3.0	5.7±0.2

Table 19. Carbon stock in substrate and plant biomass of container plants

	Pine			Spruce		
	Dry matter, g	C_{org}, %	C_{org}, g	Dry matter, g	C_{org}, %	C_{org}, g
Substrate	9.3±0.41	40.7±2.5	3.79	9.7±1.2	41.0±1.4	3.98
Below-ground biomass	0.8±0.18	48.1±1.3	0.38	1.3±0.32	47.7±0.5	0.62
Above-ground biomass	2.18±0.45	47.9±1.0	1.04	4.2±1.82	47.0±1.0	1.97

Figure 19. Pine container plant seedling (left) and a control sample without a plant from a container.

In Estonia, nearly 42 million forest tree seedlings were planted in 2023, 38 million of them were produced in Estonia. Estonian plant growers export nearly 5 million forest tree seedlings (mostly container plants to Finland and Sweden) and bare-root plants are imported. RMK renews nearly 9,300 ha of forest annually and plants 24 million seedlings, nearly 60% of them are container plants. From the seedlings planted by RMK, 10 million are spruces, 8.5 million are pines, 2.1 million are birches and 0.7 million are black alder seedlings.

Nearly 18 million trees are annually planted in private forests, 10 million of them are spruces, 4 million are pines, 3 million are birches and 0.2 million are black alders.

The typical average planting rate is 3,200 seedlings per hectare for pine, 2,200 for spruce, 2,200 for birch, and 2,500 seedlings per hectare for black alder. Pine and spruce are predominantly planted as container plants, and most often either on peat and peat-rich soil, where is a risk of frost heaving, or on drought-prone soils, where the peat substrate of the container plant helps to retain moisture and improves the survival rate of the seedlings. RMK's 60% share of container plant planting means that over 14 million container plants are planted. In private forests, the share of container plants can be estimated to 50% or 9 million trees.

A total of 23 million container plants are planted, and considering that spruces are primarily planted on peat and peaty soils with a risk of frost heaving, while pines are planted on lighter soils, it can be estimated from the distribution of forest soils that nearly 50% (10 million) of spruce container plants are planted on peat and peaty soils. Of pines, nearly 20%, or 2.5 million, are planted on peat and peaty soils.

Considering the amount of carbon contained in the root ball of each seedling (Table 18), 10 million spruce seedlings annually transfer at least 39.8 t of carbon and pine seedlings 9.5 t of carbon in the form of substrate to peatland forests. In total, 49.3 t of C is transferred to peatland forests with tree seedlings. Since peat in the substrate does not decompose differently from peat in forest soil and the carbon emissions of forest land have already been calculated based on the land use unit, indirect (off-site) emissions from such substrate should not be calculated to avoid double counting and this part should be taken into account with a 0-emission factor.

Eesti Metsameistri Taimekasvatus OÜ has adopted the principles of recycling for residual substrate generated during plant cultivation and spreads residual substrate on the agricultural lands it uses. It is conducted at 2-3-year intervals to increase the carbon content of their humus horizon and soil fertility. In 2023, the residual substrate was spread on two fields (a legume culture and a cereal field). The substrate was spread on the cereal field at an approximate ratio of 300 t/ha at outdoor humidity.

During the study, soil samples were taken from both the cereal field with substrate spreading and the area next to it without substrate spreading within the same soil contour. The carbon content in the tillage layer of the field with substrate spreading increased to 2.2±0.08%, while the carbon content in the tillage layer in the part of the field without substrate addition was 1.8±0.05%. In 2024, the C_{org} in the tillage layer of the field with residual peat spreading was maintained at 2.2±0.09%. The added substrate is qualitatively very clearly distinguished from the arable soil (Figure 20). The graph clearly shows the spectral regions were peat mineralization will occur in the future and in where the addition of fresh organic matter (roots, straw residues, stubble, etc.) occurs.

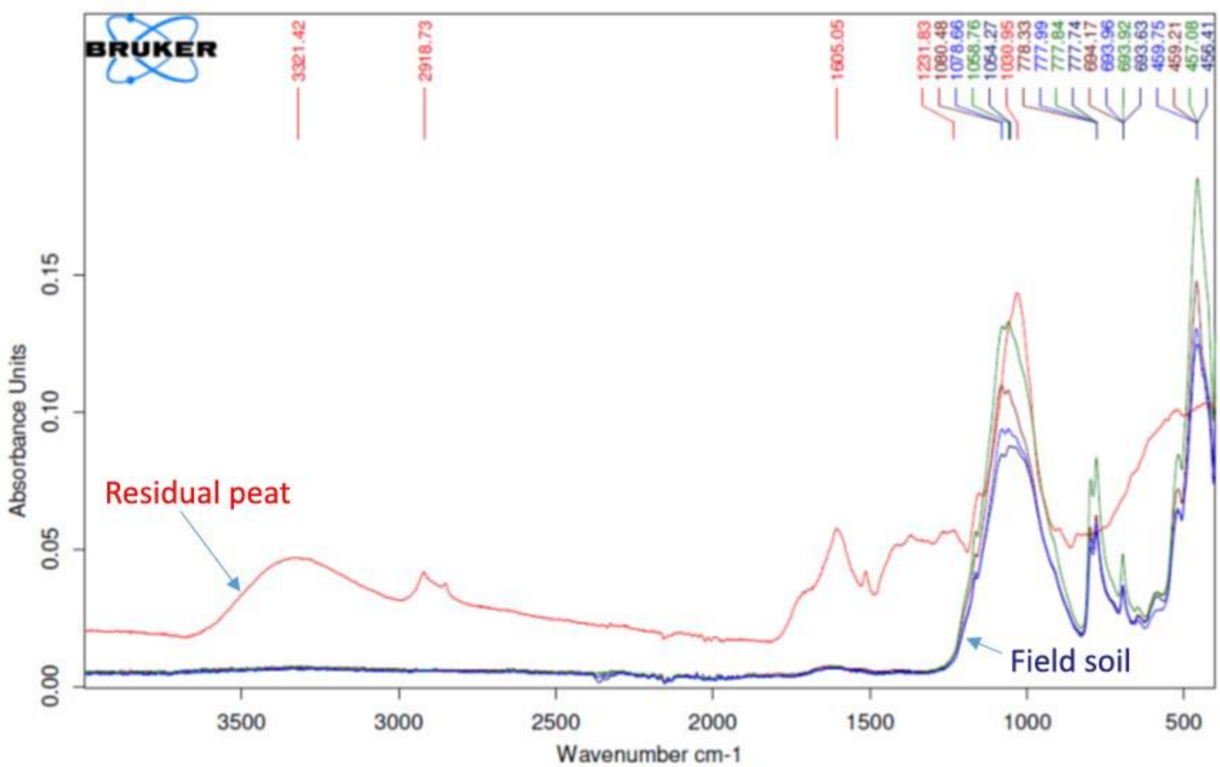


Figure 20. FTIR spectrum characterizing the qualitative difference between the residual peat substrate and the field soil, which shows that peat (red spectral line) contains significantly more difficultly decomposable organic compounds (e.g. lignin) and mineral field soil with blue and green spectral lines is sharply distinguished in the region of wavelengths 1000 and 457. The peak with a shorter wavelength is primarily associated with fresh organic matter (fine roots, straw, etc.).

Proposals for supplementing and compiling an indirect (off-site) emission factor for horticultural peat in Estonia

Although peat is widely used, the calculation of greenhouse gas emissions from the substrate in the LULUCF sector in various countries continues to be greatly simplified and the calculation takes place in the country of peat extraction, even if the peat is exported.

The Tier 1 indirect (Tier 1 *off-site*) emission factor is based on an estimate of the carbon content of peat in temperate and boreal regions; all carbon contained in peat is considered to be completely volatile to the atmosphere, and carbon emissions are considered to have oxidized immediately according to the year of calculation/declaration of the extracted quantity (Formula 1).

EQUATION 7.5
OFF-SITE CO_2–C EMISSIONS FROM MANAGED PEATLANDS (TIER 1)

$$CO_2\text{–}C_{WW_{peat_{off-site}}} = \frac{(Wt_{dry\_peat} \bullet Cfraction_{wt\_peat})}{1000}$$

or

$$CO_2\text{–}C_{WW_{peat_{off-site}}} = \frac{(Vol_{dry\_peat} \bullet Cfraction_{vol\_peat})}{1000}$$

Where:

$CO_2\text{–}C_{WW\ peat_{off-site}}$ = off-site CO_2–C emissions from peat removed for horticultural use, Gg C yr^{-1}

Wt_{dry_peat} = air-dry weight of extracted peat, tonnes yr^{-1}

Vol_{dry_peat} = volume of air-dry peat extracted, $m^3\ yr^{-1}$

$Cfraction_{wt\_peat}$ = carbon fraction of air-dry peat by weight, tonnes C (tonne of air-dry peat)$^{-1}$

$Cfraction_{vol\_peat}$ = carbon fraction of air-dry peat by volume, tonnes C (m^3 of air-dry peat)$^{-1}$

Formula 1. LULUCF indirect emission calculation formula at Tier 1 level. Source: IPCC Guidelines for National Greenhouse Gas Inventories, 2006. Chapter 7 Wetlands.

This kind of indirect (*off-site*) emission factor calculation is appropriate in case of energy peat or if horticultural peat is used as energy peat after its primary use. Although horticultural peat has been used as heating peat to a small extent by smaller plant producers in Finland in previous decades, this is not the practice today. Currently, the use of used horticultural peat as fuel is not widespread in Estonia and in none of the major export countries of Estonian horticultural peat.

The indirect emission factor for horticultural peat in this form is an extremely simplified approach that does not take into account the actual use of horticultural peat, changes in its use (both in terms of carbon content and quantity), and the amount of carbon that does not decompose and does not oxidize into the atmosphere during the after-use. Currently, these remaining carbon stocks of horticultural peat are not excluded from the emission factor.

Consequently, it is not correct to use the default values of Tier 1 for horticultural peat in Estonia, and the use of the actual carbon content value of growing peat in the reporting is more correct. At the same time, the calculation based solely on the carbon content of growing peat produced in Estonia is also a significant simplification, and in the long term, a more correct methodology for assessing carbon fluxes should be used, which takes into account the properties of growing peat extracted in Estonia (especially the actual carbon content of local peat), the intended use of horticultural peat and the actual carbon loss that occurs during its use (mainly oxidation in the form of CO_2 during decomposition), the organic matter added during the use of the substrate that remains within the substrate at the end of its immediate intended use (e.g. underground biomass in plant cultivation), and the carbon fluxes that occur during the after-use (e.g. planting container forest plants on peat soil vs. spreading residual peat on agricultural land as a soil improver).

Peat improves soil structure on both light and heavy fraction soils. Peat as a soil improver, growth substrate or residual peat in soil increases soil water holding capacity and moisture retention capacity in light fraction (sandy) soils and helps to reduce nutrient leaching (Manns & Berg, 2017). Higher and more stable soil moisture due to higher organic matter content over the year (Figure 21) in turn promotes increased bioproduction and thus an increase in soil organic carbon stock through greater organic matter input. Each soil type has its own carbon binding and storage capacity under given climatic conditions, and the accumulation of horticultural peat and residual peat occurs up to its limit. The C storage capacity of the soil is greater the more clay particles there are in the soil, the higher the soil water reserve and the more the soil has lost carbon relative to its maximum storage capacity (mostly due to tillage). There is a positive feedback between soil carbon, bioproduction and carbon storage, which is why peat introduced into the soil does not decompose completely, but rather increases the proportion of the stable fraction of the soil and contributes to the thickening of the humus horizon.

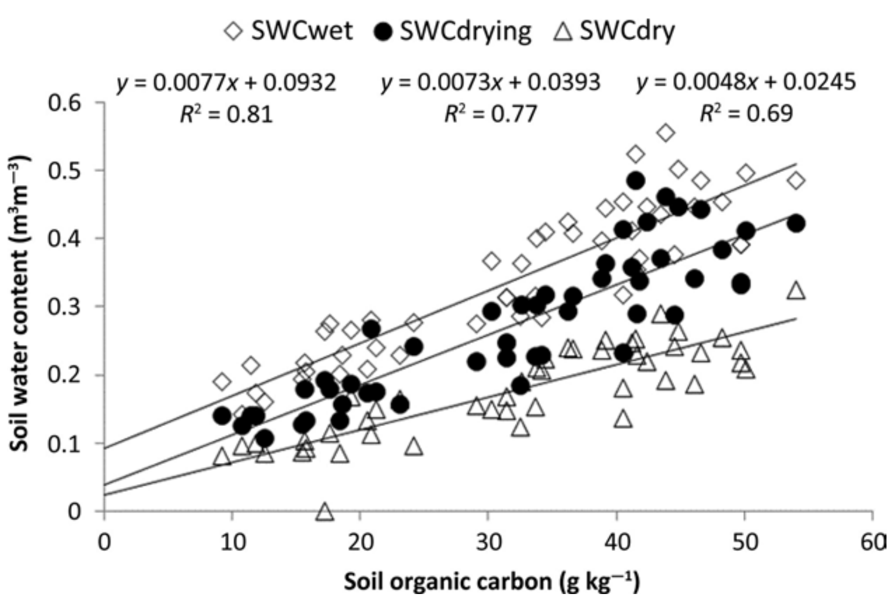


Figure 21. Relationship between soil organic carbon content and soil water availability according to soil condition (SWCwet – wet soil, SWCdrying – drying soil, SWCdry – dry soil; n = 50 significance level for all models P < 0.001). Source: Manns et al. (2016).

In the case of heavy clayey soils, peat or peat-based substrate improves soil aeration, allowing roots to breathe better and absorb nutrients. Peat also improves the buffering capacity of the soil, being a very good pH regulator, and increases the cation exchange capacity (CEC) of the soil, thereby promoting the retention of nutrients in the soil. By ensuring more uniform nutrient availability to plants, bioproduction increases (more aboveground and belowground biomass is generated) and leaching of fertilizers/nutrients is prevented. At the same time, peat is helping to maintain or increase the soil organic carbon stock (in the form of litter and humus). Soil organic carbon (SOC) content increases soil water content according to the equation shown in Figure 22.

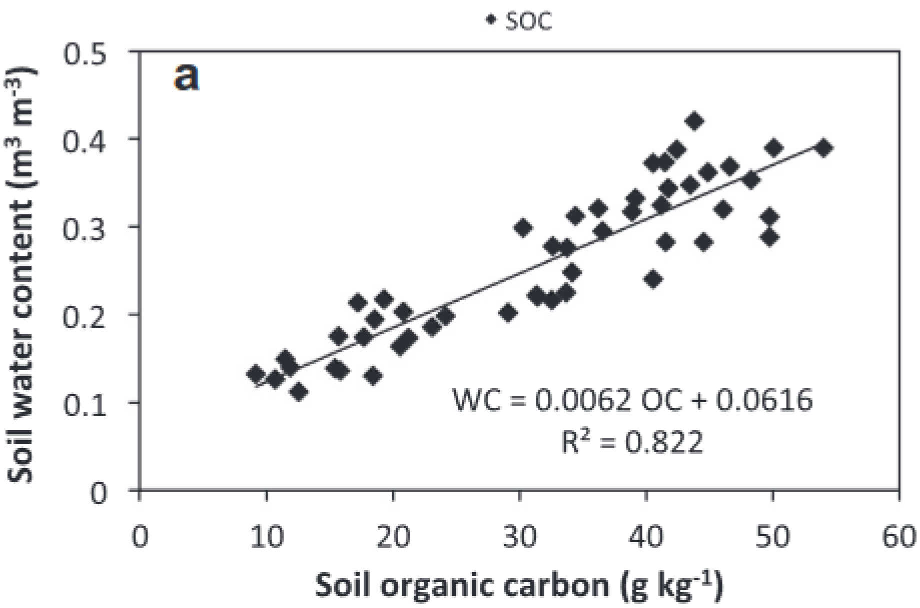


Figure 22. Soil water content in mineral soils is linearly related to soil organic carbon content (Manns et al., 2014).

A 1% increase in soil organic carbon is equivalent to an increase in water holding capacity of approximately 2%. Thus, in a soil with a water holding capacity of 200 mm, an increase in organic carbon content increases water holding capacity by another 4 mm.

Similar to an increase in water holding capacity, an increase in the organic carbon content of mineral soils also improves bioproduction and yield. Higher bioproduction, in turn, ensures the maintenance of soil carbon stocks in the form of additions to below- and above-ground litter. At a global level, and focusing specifically on the potential impact of soil organic carbon (SOC) on yield, Oldfield et al (2019) found that the greatest yield increases occur in the SOC range of 0.1–2.0%. For example, yields are 1.2 times higher at 1.0% SOC than at 0.5% SOC. Yield increases level off at around 2% SOC. The study also found that around two-thirds of the world's cultivated land for maize and wheat currently has a SOC content below 2%, and thus a higher carbon input (e.g. in the form of residual peat) would help restore or improve soil fertility.

The biomass (dry matter) formed during the annual growth cycle of the large-scale crops (maize and wheat) ranges from 9.7 to 19.2 t/ha for wheat and 26-32 t/ha for maize (Major et al., 1986; Maucieri et al., 2019; Pärnamäe, 2024). Considering the potential 20-30% increase in bioproduction with a 1% increase in soil carbon stock, the additional long-term carbon sequestered by plants during each growth cycle (2.9-9.6 t/ha) is of great importance for the carbon cycle associated with the use of residual peat, which deserves more in-depth investigation.

Using data from 13,662 field trials with 66,593 different soils, climates and management practices, Ma et al. (2023) show that yield increases with increasing soil organic carbon, up to soil organic carbon levels of 43.2–43.9 g kg^{-1} (4.32–4.39%) for maize, 12.7–13.4 g kg^{-1} (1.27–1.34%) for wheat and 31.2–32.4 g kg^{-1} (3.12–3.24%) for rice, and no further significant increase ($p < 0.05$) above the average optimum level in fertility increases. Thus, regardless of the region of export of the horticultural peat, the use of residual peat as a soil amendment or planting the pre-grown plants with peat in the soil has significant potential to increase soil fertility, as current SOC levels in cultivated land are almost everywhere well below the optimum level.

The change in the soil organic carbon balance is characterized on Figure 23. The potential of the soil to store organic carbon is based on its ability to protect (i.e. stabilize) SOC. Organic carbon is protected from microbial decomposition by the adsorption of organic compounds on the surfaces of mineral particles (pores less than 0.2 mm in diameter) and by binding in soil aggregate particles. In soils with heavier interstices, clay particles act as a protection for organic matter from microbial decomposition. In contrast, SOC is more rapidly cycled in soils with low clay content, therefore it is more difficult to increase SOC content in coarse-textured sandy soil with crop residues alone, and the water regime is also less favorable and the effect of added peat is greater. However, peat is better preserved in the long term in clay-rich soils.

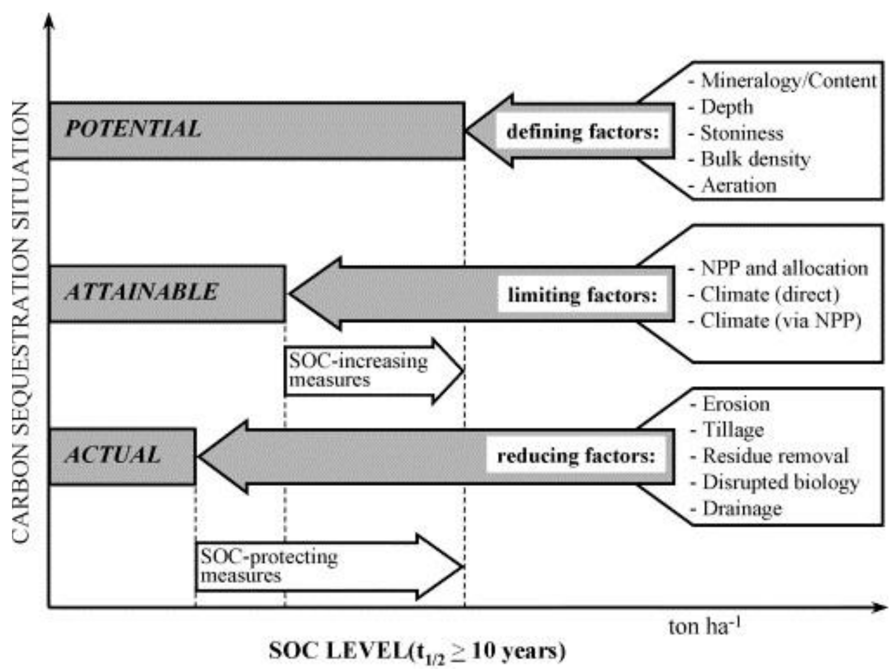


Figure 23. Relationship between actual, attainable and potential soil organic carbon as a function of influencing factors and carbon input or reducing factors. Source: Ingram and Fernandes (2001).

In general, studies show that every 1% organic carbon addition below the optimum level can increase yield by 10-30% or more, but this varies considerably depending on the factors mentioned above (Figure 23). Increasing organic carbon in the soil can increase yield through several mechanisms:

1. Improving soil structure: The presence of organic matter helps to improve soil structure, making it more aerated. Good structure improves root aeration and water movement, which is essential for plant growth.

2. Regulating water content: Organic carbon increases the water-holding capacity of the soil. This means that soil moisture can be better retained, which is especially important during periods of low rainfall and on drought-prone soils.

3. Increased nutrient availability: Organic matter is a natural source of nutrients, including nitrogen, phosphorus and potassium. Increased organic carbon contributes to microbial activity, which in turn promotes the release of nutrients through mineralization, making them more readily available to plants.

4. Microbial activity: Organic carbon supports the life of soil microorganisms, which is necessary to maintain soil quality and fertility. Microbes help to decompose organic matter and release nutrients that can be used by plants.

On the one hand, the introduction of peat into the soil helps to increase the carbon stock of the soil and thereby improve bioproduction and increase the volume of the carbon cycle. On the other hand, it inevitably leads to partial mineralization of the peat. The decomposition of peat and the preservation of residual peat in the soil depend on several factors, including soil type, moisture conditions, temperature and acidity. Also on the chemical composition and degree of decomposition of the peat. Peat is rich in lignin, cellulose and hemicellulose, which are relatively slowly degradable compounds, and lignin is one of the main inputs to the humus formation of the underground root stock of herbaceous biomass. Changes in soil organic carbon due to land use or management practices are at least partly dependent on previous land use and thus show a 'legacy effect' (Foster et al., 2003), which may help to explain changes in soil C stocks. For example, it is widely accepted that C accumulation is faster when land use change involves a transition from cultivated (disturbed) soils to permanent grasslands. It is assumed that under continuous agricultural practices (e.g. 50–100 years after a land use/management change) and at a depth of 0–30 cm, grassland soil C eventually reaches a steady state, and that as C content approaches this steady state, the rate of C accumulation decreases (Smith, 2014). However, it is not clear when soil SOC accumulation can reach a new steady state, mainly because it depends on the interaction of climatic factors and management practices (i.e. grazing, fertilization, liming, reseeding, etc.). Moderate additional organic matter input (e.g. residual peat, residual peat with composted plant residues) accelerates the achievement of stable SOC levels in depleted arable soils and thereby increases the long-term soil carbon stock.

Tier 2 and Tier 3 indirect (off-site) emission factor applicable to Estonia

The international greenhouse gas emission accounting rules allow the use of national factors at the second level of accounting. Accordingly, it is appropriate for Estonia to use the peat organic carbon content values determined by laboratory studies during 2023-2024 for peat extracted and processed in Estonia, and to regularly update these values at least after every five years, since the properties of extracted peat change over time within the depth profile of the extracted layers in the production areas. Although the laboratories use a similar ISO standard for both sample pre-treatment and the analytical process (ISO 11464:2006 and ISO 11465, respectively), the difference in the determinations is significant and therefore, for the sake of international comparability, it is recommended to use the average value of all laboratories as the peat organic carbon content (47.4% ± 1.12) (Table 20).

Table 20. Average organic carbon content (org C, %) of peat extracted in Estonia and degree of peat decomposition (von Post H) in the sampled peat extraction sites based on an area-average sample collected from the sites

		METK	**EKUK**	**TÜ**	**EMÜ**	**Mean**	**StDev**
Site	**Von Post H**	**Org C, %**	**Org C, %**	**Org C, %**	**Org C, %**	**Org C, %**	**Org C, %**
Site1	H5	43.4	48.0	49.0	45.8	46.6	2.49
Site2	H5	45.9	49.0	52.3	43.8	47.8	3.71
Site3	H4	44.9	50.0	51.5	46.8	48.3	3.00
Site4	H6	44.7	49.0	49.7	46.6	47.5	2.29
Site5	H6	45.0	49.0	49.2	47.4	47.7	1.94
Site6	H5	46.6	50.0	47.9	46.7	47.8	1.58
Site7	H6	44.8	49.0	48.5	46.6	47.2	1.92
Site8	H6	41.9	47.0	49.6	43.2	45.4	3.53
Site9	H4	44.3	48.0	45.4	47.5	46.3	1.75
Site10	H7	46.5	50.0	52.6	46.9	49.0	2.86
Site11	H6	46.6	52.0	51.9	43.5	48.5	4.18
Site12	H4	42.3	47.0	50.2	45.2	46.2	3.31
Site13	H5	46.4	50.0	52.4	47.0	49.0	2.79
Site14	H6	44.6	49.0	47.4	43.7	46.2	2.46
Mean		44.9	49.1	49.8	45.8	**47.4**	
StDev		1.52	1.33	2.14	1.57	**1.12**	

The carbon content given in Table 20 is the base value; according to this the emissions of horticultural peat with a relative humidity of 40% are determined. While reporting national greenhouse gas emissions, the average organic carbon content of horticultural peat extracted in Estonia may change over the years, depending on whether more weakly decomposed or well-decomposed peat is extracted. In addition, it is important to pay attention to determining the lignin, hemicellulose and cellulose content of the extracted horticultural peat in order to more accurately estimate the actual peat decomposition rate in Tier 3 calculations. The higher the lignin content of horticultural peat, the slower the substrate decomposes and the more organic carbon remains permanently as part of the soil humus, which should not be declared as emissions.

In relation to greenhouse gas emissions related to carbon transfer from peat production, it is necessary to consider them *on-site*, i.e. in relation to the production area, and *off-site*, in relation to the use of extracted peat. The methodology for direct emissions, i.e. in relation to the extraction area, is quite well developed and in this regard, a more accurate estimate of the actual flux is necessary, in particular, in accordance with the current state of measurement technology and modelling capabilities.

Since emissions have a direct impact on political decisions, it is important to separate the emissions of the current peat sector from the emissions of historical production. This is quite simple using geodatabases and statistical databases, and the development is relatively inexpensive. The Land Board keeps records of the area of mining plots with an accuracy of 0.01 ha. The historical areas of mining plots can also be extracted or, if necessary, derived with high accuracy. Based on orthophotos, it is also possible to analyze the historical occupation of mining plots, especially the construction of new areas. According to the stockpiles or changes in coherence due to the production process with remote sensing solutions (e.g. based on the cloud-independent Sentine-1 SAR dataset, see Tampuu et al., 2021), it is also used if necessary. The part of existing mining plots needs to be separated from the general part of the statistical forest inventory (SMI) as accurately as possible. No more areas from current production will be added to the so-called historical production. The production areas will be included in the mining plots in a regulated and certified state in accordance with the conditions set out in the extraction permit. Until there are newer on-site emission factors, it is appropriate to use the Estonian-based values used so far.

Areas historically used for peat extraction can continue to be used on the basis of SMI if necessary, but it is also possible to specifically delimit these areas based on a revision carried out by the Geological Survey of Estonia and with a simple geoinformatics check and then assign them to emission and/or sequestration classes depending on their current state (e.g. forested, swampy, without complete vegetation cover). It is important that all former peat extraction sites that have been restored, are included into the statistics with actual carbon flux values and are included in the on-site calculation. It is possible to distinguish naturally regenerated areas using remote sensing (via indices indicating vegetation and vegetation characteristics - mosses, sedges, reeds, stands - and LIDAR vegetation cover models).

To determine indirect emissions, the domestic consumption of energy peat and the exported energy peat (to Sweden and Finland) and then the peat used as horticultural peat must be subtracted from the peat extracted in Estonia. The quantities that do not actually decompose (substrate that is transferred to peat soil, e.g. forest container plants for planting on peat soils) and remain stored in the soil as organic carbon in the long term, must be subtracted. In the case of indirect emissions of energy peat, it is appropriate to apply the instant oxidation methodology, i.e. the calculation of emissions could continue according to the current methodology.

Double counting of horticultural peat must also be avoided, e.g. if the extracted horticultural peat is first considered to have completely oxidized as carbon dioxide, but in reality it ends up in forest and fruit tree seedlings, vegetable and ornamental plants and as residual peat in agricultural soils, where it compensates for the carbon lost during intensive land cultivation and is stored as a stable organic carbon fraction of the soil.

Direct use of horticultural peat is short-term (3 months - 3 years, on average 1 year) and during direct use, carbon loss is ~2% per year of the original organic carbon content of the peat.

Similar to the results of the present study, where the direct use of horticultural peat results in a carbon loss of 0.9-16% of the initial carbon content, with an average of 2% over the period of use, Cleary et al. (2005) used an average annual decomposition rate of 5% for peat-based substrates in Canada. The authors acknowledge that the actual range in the first year is 0-6%, in some cases even nearly 10%, but the higher values are related to the fact that in this case the peat is mixed with other organic compounds in the substrate (e.g. compost) and it is no longer possible to distinguish the proportion of peat and compost during decomposition. The study by Cleary et al. (2005) also does not address the long-term decomposition of the growing substrate and the transformation of the carbon in the peat when it is introduced into the soil after use (landscape design, pre-grown plants planted in the soil, use of residual substrate as a soil improver). Therefore, in all cases the decomposition rates correspond to the decomposition rate of the product (substrate) during its immediate use as a substrate, and not to the decomposition rate estimated using the cradle to grave method. The latest studies by Sharma et al. (2024) and Sharma and Roulet (2024) (Carbon Management, in press) indicate a cradle to grave decomposition rate of 0.6% of the carbon in the horticultural peat per year.

A study conducted in Japan by Murayama et al. (2012) also found that peat-based substrate decomposes by 1.8-3.7% per year, depending on the nitrogen content and composition (sedge peat, sedge-*Sphagnum* and *Sphagnum* peat), and when a mineral component or straw is added to the substrate, the decomposition rate of the substrate increases to 9-11% per year. In the case of peat, the main part of the decomposition volume is lignin, which is the most abundant in the substrate by mass, but at the same time it is the slowest decomposing part of the substrate. However, the saccharide group decomposes the fastest in peat-based substrates, though its content decreases gradually as the peat is more decomposed. Wheat straw decomposes in the substrate by nearly 77% in a year. Therefore, the emission of greenhouse gases (mainly in the form of CO_2) from substrates with compost additives is higher than that of peat-based growing substrates alone.

When the peat moves to soil with a seedling or as a residual substrate, the consumption of domestic growing peat does not lead to a decrease in the carbon stock, but the residual peat (and the organic carbon contained in peat) becomes an input to the soil's organic stock as an organic additive, similar to manure, green manure and underground biomass. The added peat (mainly in the form of animal bedding peat on large farms, declared as organic fertilizer/manure) has already increased the carbon stock of Estonian agricultural soils over the previous decades (mainly in the 1960-1990 period) (Loide & Edesi, 2021) and has largely not decomposed to date.

Residual peat introduced into agricultural and forest soils (and bedding peat as part of organic fertilizer/manure) is already reflected in both the soil carbon stock and the area-based emission factor for agricultural land and forest land - this is standard economic practice and all estimates of gas fluxes related to agricultural land and forest land implicitly include the peat carbon added to the soil and its very slow decomposition in the area-based emission calculation (peat ball for container plants, peat ball for fruit and ornamental plant seedlings, peat ball for vegetable plants or residual peat as a soil improver/manure component) (Kauer and Astover, 2024; Hyvonen et al., 1996; Karhu et al., 2012).

In the 100-year perspective, the undecomposed residue (29%) of the initial carbon content of peat can be considered as an estimated stable part of the organic carbon of the soil humus horizon (Kauer and Astover, 2024). This must not be considered an emission because it is an addition of an organic additive/input (peat, residual peat after crop cultivation, residual peat as part of composted organic waste) and transforms into a part of the humus horizon (the humus horizon thickens and the organic C content increases until a natural equilibrium state is reached according to the characteristics of the climate, source rock and land cultivation/use methods).

The undecomposed stable carbon added to the humus horizon (29% of the original peat organic carbon) has been modeled with the RothC model according to the characteristics of Estonian growing peat (Kauer and Astover, 2024: Table 1, EEC org C determination), Estonian climatic data and the soil properties of Estonian arable land (especially the content of clay particles, which is the most important factor affecting the preservation of the org C stock in the soil). Therefore, this result is suitable for use in preparing Tier 3 level estimates. This is a rather conservative estimate because the peat org C value determined by the EEC is lower than the average value of the 4 laboratories and the input is therefore estimated lower. For pan-European use in the context of the main target markets (the Netherlands and Germany, 43% of the peat exported from Estonia in the last 5 years), a similar undecomposed residue (29%) can be used since this is a Northern European region. Alternatively, the result modeled with the default values of the RothC model (13-15.2%) can be used as a conservative estimate until the results are modeled based on the actual climate and soil of the main target countries. Certainly, 13-15.2% of undecomposed peat organic carbon is a conservative estimate for European target markets, as it is identical to the results of a long-term Swedish experiment (Hyvonen et al., 1996; Karhu et al., 2012), but the peat decomposition rate used in the experiment was significantly faster (in Sweden, IROC = 65.2%, which corresponds more to the manure/organic fertilizer decomposition rate IROC = 49.2-68.9% (Peltre et al., 2012) than to the Estonian peat IROC = 87.4% (Kauer and Astover, 2024)).

In the case of exported horticultural peat, the carbon in the peat also reaches the soil during vegetable cultivation (over 82% of Estonian exported peat), ornamental plant and tree nurseries, and landscaping. The carbon stock of residual peat stored in the soils of the main export countries will need to be modeled in a similar way to Kauer and Astover (2024) did with Estonian data. However, the intensive use of agricultural land in the main export countries (Netherlands, Belgium, Germany, France, Spain, China, Poland, Turkey) and their significantly lower level of carbon content compared to the natural background of carbon than in Estonian agricultural soils (LUCAS, 2018; Froger et al., 2024) have to be considered. Therefore, the potential for carbon storage of residual peat substrates in these soils is high (Figure 24).

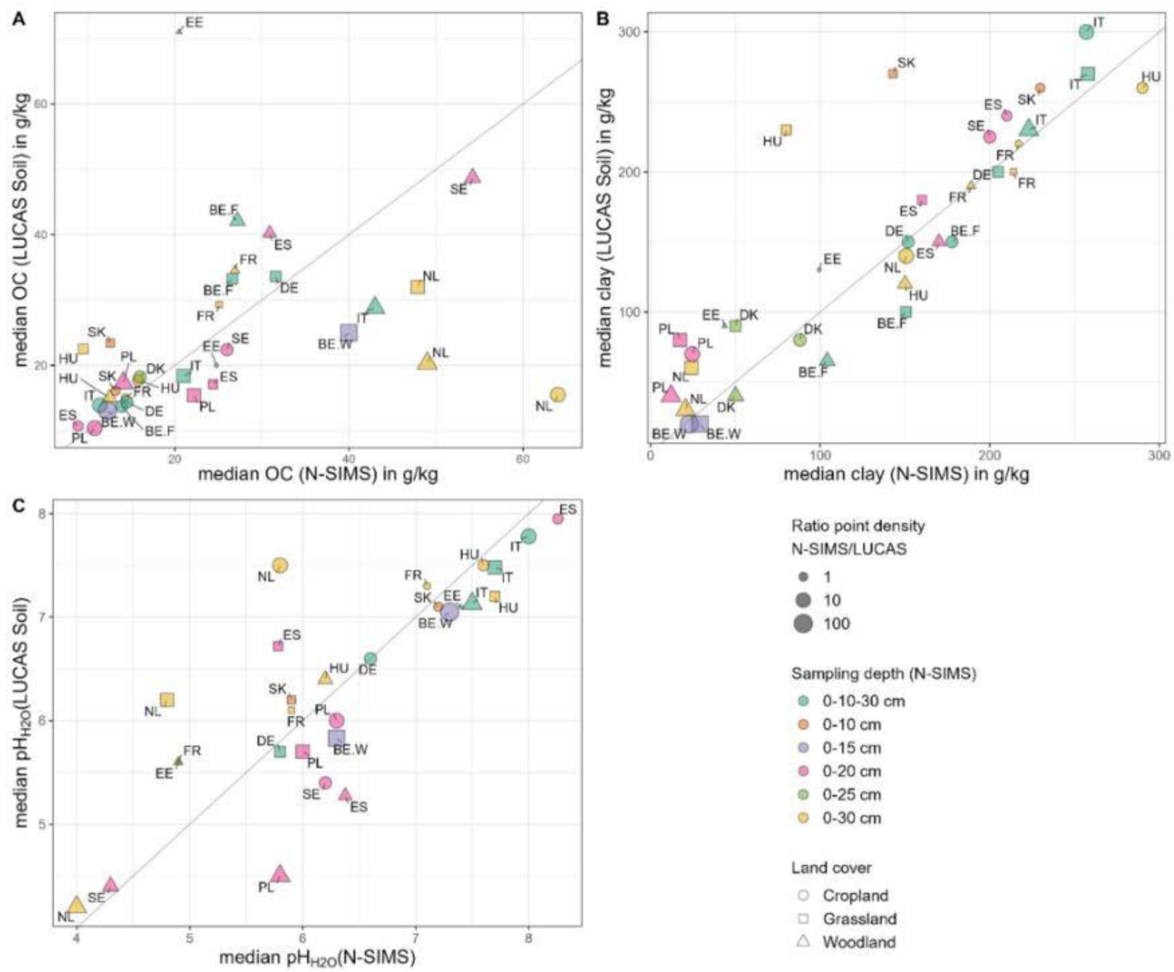


Figure 24. The correspondence between the LUCAS pan-European soil database and national monitoring programmes for soil organic carbon, clay content and soil acidity and their usability as a baseline dataset for modelling residual peat to be stored (LUCAS, 2018; Froger et al., 2024).

Since 1990, 25 million t of peat have been exported from Estonia at actual moisture and mass, and it continues to be stored to a large extent in the agricultural soil of the export countries as a soil carbon stock. In terms of extraction volume, this corresponds to an estimated 15-20 million t of air-dry (40% relative humidity) peat. Similarly to Estonia, it must be taken into account also in the case of exported horticultural peat that the (residual) peat introduced into agricultural soil with plants and seedlings partially decomposes and greenhouse gases are calculated on an area basis, thus double counting occurs.

For Tier 3 emissions, it would be more objective from a carbon cycle perspective to use time-dependent oxidation model, as peat decomposition is naturally very slow process, with an annual decomposition rate of 0.6-1.7% of the original carbon stock (Hyvonen et al., 1996; Karhu et al., 2012; Sharma et al., 2024; Sharma and Roulet, 2024). In this case, the calculation would also be more consistent with the time frame for assessing the carbon flux associated with real land use and the management of extraction areas. However, this type of calculation introduces the problem of potential dispersion of responsibility and the assessment of emissions related to peat that was extracted in the past and reached the soil but was not fully decomposed.

Summary

The European Union has set a goal of achieving climate neutrality by 2050, to which all sectors must contribute. As a result of Regulation 2018/841 of the European Parliament and of the Council (hereinafter LULUCF Regulation), the land use and forestry sector, which also includes managed wetlands and peat production, will be included in the European Union's energy and climate policy framework, and instead of reporting the current data, a stricter accounting system related to the national GHG reduction obligation will be implemented for greenhouse gas (GHG) emissions from the activities of this sector.

Estonia is one of the world's leading producers and exporters of horticultural peat and growing media. In order to maintain the economic sector and its export capacity, it is important to more accurately assess and reduce emissions associated with horticultural peat production through the implementation of circular economy and sustainable carbon cycle principles and new practices. The aim of this study is to identify the areas of use of Estonian horticultural peat, export countries and the after-use of horticultural peat. The changes in carbon content, biomass production and greenhouse gas emissions associated with the use of horticultural peat, both in the laboratory and with substrate users, were also studied experimentally. Based on the measurement results, indirect greenhouse gas emissions were specified for the main plant cultures and opportunities for using residual substrate with minimal greenhouse gas emissions and based on the principles of the circular economy were assessed.

Giving added-value to horticultural peat extracted in Estonia begins with sieving and dividing the peat into fractions, followed by additional valorization with additives, the most important of which in terms of volume are expanded perlite, wood fibers, sand and clay, lime, coconut fiber and compost. The final substrate accounted in 2022 for approximately one quarter of peat products produced in Estonia, but this share is rapidly increasing. A significant part of the horticultural peat is exported as milled peat that has been screened and neutralized with lime, or as the so-called base substrate.

The study revealed that the main use of horticultural peat produced in Estonia takes place outside the country of production. The largest destination countries for horticultural peat are the European Union member states, but China's share is growing rapidly, and Turkey and Morocco are also important importers.

The vast majority (82%) of exported horticultural peat is used in vegetable cultivation. Consequently, a large part of the peat used also ends up in the form of seedlings or residual peat in the agricultural soil, where it increases the carbon reserves of the soil depleted during intensive agriculture. The use of exported horticultural peat for vegetable cultivation is greatest in China and the Mediterranean countries; in addition to vegetable cultivation, peat from Estonia is also important for the cultivation of ornamental plants and tree seedlings in the Netherlands and for mushroom cultivation in Germany and the United Kingdom.

In Estonia, a significant part of the peat is used for the cultivation of summer and perennial flowers, fruit and ornamental trees and shrubs, as well as peat is used for landscaping and the cultivation of forest plants.

The direct use of horticultural peat is short-term and the emissions generated in the process are modest. Carbon loss occurs almost entirely as carbon dioxide, while methane and nitrous oxide emissions are insignificant. This is also in good agreement with other previous studies. The highest emissions are

associated with vegetables grown in well-aerated conditions and bulbous flowers, but their growing period is very short and therefore the total emissions during direct use are modest. Calculation of the indirect (off-site) emissions must take into account that the main carbon oxidation and emission as greenhouse gases occurs during the subsequent use of the substrate. The main method of after-use, both in Estonia and in export markets, is the direct or post-composting transfer of the residual substrate to agricultural soil.

A significant part of the substrate also goes to agricultural soil directly with the root ball of vegetable plants or as container plants and seedlings, and the peat substrate becomes part of the soil. In the perspective of 100 years, the non-degradable residue (29%) added to the soil can be considered as an estimated stable part of the organic carbon of the soil humus horizon from the initial carbon content of the peat. This part is not a basis for considering emissions, because it is an addition of an organic additive/input (peat, residual peat after plant cultivation, or residual peat in the composition of composted organic waste) and it transforms into a part of the humus horizon (the humus horizon thickens and the organic C content increases until a natural equilibrium state is reached according to the characteristics of the climate, source rock and land cultivation/use methods).

While calculating the indirect emission of growing peat, attention must be paid to the fact that the part of the peat-based substrate transferred to peat soil with (forest) plants is not included in the emissions, because the carbon content of the substrate in peat and peat-covered soil does not change differently from the surrounding environment.

Direct use of horticultural peat is short-term (3 months - 3 years, estimated on average up to 1 year) and during direct use, carbon loss is approximately 2% per year of the original peat substrate organic carbon content. When substrate moves back to the soil with a plant or as a used substrate residue, the consumption of domestic horticultural peat does not lead to a decrease in the carbon stock, but the residual peat (and the organic carbon contained in the peat) becomes an input to the soil organic stock as an organic additive, similar to manure, green manure and underground biomass. Peat added to agricultural soil over the years (mainly in the form of animal bedding peat on large farms, as declared organic fertilizer/manure, less as horticultural peat with plants and as a soil improver) has already increased the carbon stock of Estonian agricultural soils over the previous decades (mainly in the 1960-1990 period) (Loide & Edesi, 2021) and has not decomposed to a large extent so far. Residual peat introduced into agricultural and forest soils is already perceptible in both the soil carbon stock and its interannual change, and therefore also in the emissions of agricultural land and forest land calculated based on the area-based (soil) carbon stock change - this is standard economic practice and all estimates of gas fluxes or soil carbon stock related to agricultural land and forest land are indirectly included in the area-based emission calculation. Peat balls of container plants, fruit and ornamental plant seedlings, and of vegetable seedlings or residual peat as a soil improver and in the composition of manure have been added to the soil as peat and have increased its carbon stock. Its very slow decomposition is also highlighted by the change in soil carbon stock if additional organic additives are not added to the soil in the case of standard land use (Kauer and Astover, 2024; Hyvonen et al., 1996; Karhu et al., 2012).

In a 100-year perspective, the non-degradable residue (29%) of the original peat carbon content can be considered as an estimated stable part of the soil humus horizon organic carbon (Kauer and Astover, 2024). This must not be considered an emission because it is an addition of an organic additive/input (peat, residual peat after crop cultivation, residual peat as part of composted organic waste) and its transforms into a part of the humus horizon (the humus horizon thickens and the organic C content increases until a natural equilibrium state is reached according to the characteristics of the climate and source rock and land cultivation/use methods). The non-degradable stable additional carbon to the humus horizon (29% of the original peat organic carbon) has been modeled with the RothC model according to the characteristics of Estonian horticultural peat, Estonian climatic data and the soil properties of Estonian cultivated land (especially the content of clay particles), which is the most important factor affecting the preservation of the soil organic carbon stock in the soil.

The undecomposed residue result is suitable for use in preparing Tier 3 level assessments. This is a rather conservative estimate as the peat org C value determined by the EEC is lower than the average value of the 4 laboratories and the input is therefore estimated lower. For pan-European use in the context of the main target markets (the Netherlands and Germany, 43% of the peat exported from Estonia in the last 5 years) a similar undecomposed residue (29%) can be used as this is a Northern European region. Alternatively, as a conservative estimate, the result modelled with the default values of the RothC model (13-15.2%) can be used until the results are modelled based on the actual climate and soil of the main export countries. 13-15.2% of undecomposed peat organic carbon is certainly a conservative estimate for European export markets, as it is identical to the results of a long-term Swedish experiment (Hyvonen et al., 1996; Karhu et al., 2012), but the decomposition rate of the peat used in the experiment was significantly faster (in Sweden, IROC = 65.2%, which corresponds more to the decomposition rate of manure/organic fertilizer, IROC = 49.2-68.9% (Peltre et al., 2012) than to the Estonian peat, IROC = 87.4% (Kauer and Astover, 2024)).

In the long term, it is important to reach a situation in reporting indirect emissions of peat use, where carbon emissions are calculated at the consumer level (similarly to e.g. liquid fuels). This ensures consumer responsibility and motivates for efficient after-use. It would help to make critical choices and political decisions, if thorough life cycle analyses of horticultural peat would be made. These should include the duration from cradle to grave instead of the current cradle-to-gate or cradle-to-end-of-life method.

Since not all horticultural peat decomposes, large extent of the exported peat from Estonia continues to be stored in the agricultural soil of the export countries as soil carbon stock. However, it is declared in Estonia as an emission using the instant oxidation method. The European-wide cumulative error resulting from the production and export of horticultural peat in Estonia alone and its use in other export countries is estimated at 15 million t CO_2 eq., which is a significant amount and certainly deserves attention. At the same time, a significant part of this horticultural peat continues to be stored in the soil of the European Union as soil organic carbon without being emitted. Is a normal part of the usual agricultural practices of the respective countries and has a positive impact on the change in soil carbon stock.

While reporting national greenhouse gas emissions, it is important to keep in mind that the average organic carbon content of horticultural peat extracted in Estonia may change over the years, depending on whether more weakly decomposed or well-decomposed peat is extracted. In addition, it is important to pay attention to determining the lignin, hemicellulose and cellulose content of the extracted horticultural peat in order to more accurately assess the actual peat decomposition rate in Tier 3 calculations. The higher the lignin content of horticultural peat, the slower the substrate decomposes and the more organic carbon remains permanently as part of the soil humus - that should not be declared as emissions.

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