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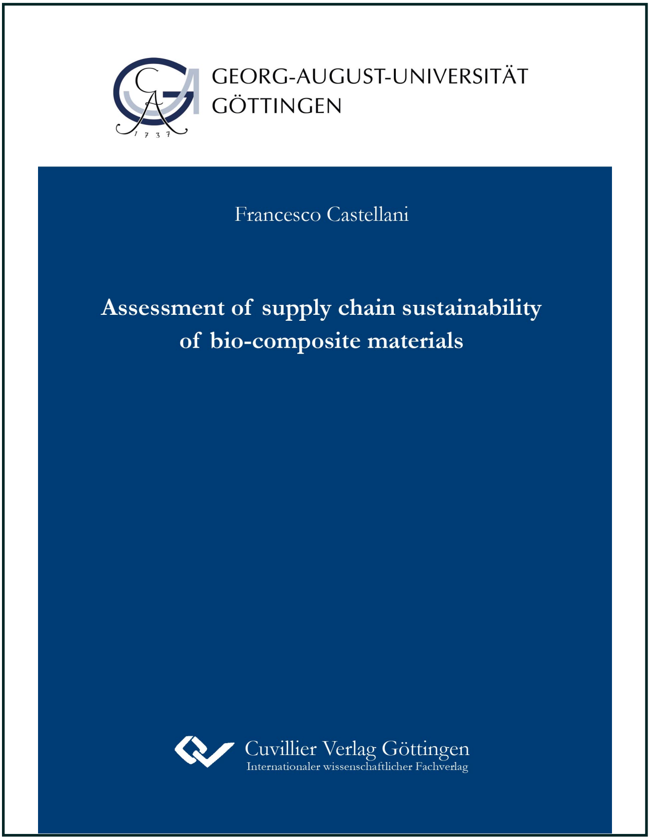
Assessment of supply chain sustainability of bio-composite materials



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1 Introduction

Industrial processes are currently based on considerable consumption of fossil resources. Bringing down the level of greenhouse gases (GHG) emitted into the atmosphere when extracting and processing this kind of resources has been a main driver for the development of fossil resources substitutes (e.g., bio-based, biodegradable materials) and for the adoption of strategies to promote their efficient use. The European Commission, for instance, proposed a joint Statement on cascade use of wood (AEBIOM et al., 2013), in order to promote active forest management and improve resource efficiency (Geldermann et al., 2016a). However, the choice between conventional fossil-based materials and bio-based ones requires the consideration of many aspects along the supply chain. Supply chain optimization, increment of efficiency and product quality, reduction in GHG emissions, and reducing costs are only some of the goals that decision-makers must face to maintain and increase business competitiveness. This situation concerns any production system, both in industry and agriculture. The horticulture sector, a relevant sub-sector of agriculture, deals with the cultivation of edible products (e.g., fruit and vegetables) and ornamental products (e.g, decorative plants, trees, potted plants, and cut flowers). Recently, it has been realized that the supply chain of current production system in horticulture settings could be improved to reduce costs and emissions (Lazzerini et al., 2016). Horticultural market requests, indeed, a change, and it asks for the introduction of innovative, more sustainable products. However, crops cultivation is influenced by many factors, such as biological aspects (e.g., pathogens) and external factors (e.g., weather), which determine high vulnerability to risks. Growers, horticulturists, and plant nursery decision-makers face therefore the challenging task of choosing between conventional fossil-based resources and their substitutes.

Peat is a non-renewable fossil-based resource accumulated over millions of years in peatlands. The extensive exploitation of peatlands to extract peat as fuel or growth medium has remarkably reduced the global carbon storage (Gorham, 1991), and it has consequently raised environmental concern (Schmilewski, 2013). Peatland protection aims to maintain both biodiversity and such ecosystem services as climate protection and nutrient retention. However, peat is currently the main component of growth substrate for cultivating plants in horticulture. To preserve the environment from the massive use of this fossil-based resource against GHG emissions increase, limitation to peat utilization has been introduced in some European Countries (e.g., Niedersächsisches Ministerium für Ernährung, 2017). Consequently, horticultural decision-makers started to investigate and test peat substitutes for cultivating plants, and agro-waste compost is a promising suitable resource towards this end. Along with other agricultural media, compost can be mixed with sphagnum peat to form growth substrate for potted and field-grown plants. The substitution could lead to reduction in GHG emissions caused by the horticulture sector. In horticulture, another environmental concern is the plastic waste management of pots used for cultivating. Since they cannot be recycled easily due to soil and vegetable matter contamination, agrochemical residues and additives, they are generally landfilled after one usage (Schettini et al., 2013). Here, biodegradable pots made of renewable resources, which can be embedded in the soil with the plant or disposed of in composting facilities, represent a viable alternative to plastic pots. Both novel materials, compost and bio-based pots, can reduce the environmental emissions of a company and attract customers with willingness to pay for these more environmentally-friendly products. By doing so, plant nurseries might improve their image and become more competitive.

However, when mixing peat with compost beyond a certain replacement percentage, the agronomic quality of a potted plant becomes unacceptable, and substituting for peat may also result in higher costs for processing and handling. Moreover, biodegradable pots have higher costs than plastic pots. These aspects introduce conflicting goals for the decision-maker: reducing the environmental impacts and at the same time reducing additional costs that incur when substituting for peat and plastic pot.

This leads to the following research question: *Can decision-makers of plant nurseries substitute innovative, bio-based materials for conventional ones and improve the environmental sustainability of potted plants and at the same time minimizing the additional costs?*

The question of this thesis arises whether optimal mix of substrate (composed by peat and compost) and optimal material of planter container (e.g., fossil-based plastics or biodegradable, bio-based polymer) can be determined, such that additional costs when substituting and environmental impacts of a potted plant are simultaneously minimized—this is the *decision problem* of this dissertation. To answer to this question and find the trade-off between emissions and costs, approaches of Operations Research (OR) can be used. In general, emissions and costs relevant to the decision—which are different between the alternatives—should be taken into account. This thesis, which combines different disciplines, such as environmental engineering, agronomy, and business administration, is structured as follows.

Chapter 2 explores the value chains of peat, compost, and plastics in horticulture. Here, the following concepts are introduced: sustainability, peatland protection, waste management of plastics, cascade use of resources, resource efficiency, and substitutes for peat and plastic pots.

Peat, olive-mill waste compost, plastic pots made of polypropylene, and pots made of polylactic acid are the four case-specific technical solutions of the decision problem.

Chapter 3 describes methods to assess the environmental burdens of resources used in agriculture. Critical aspects and studies reported in literature are highlighted. A sustainability assessment of the supply chain of the technical solutions is preformed via Life Cycle Assessment (LCA). The analysis follows GHGs experimental detection of bio-based materials. These activities, which consist of hardware assembly, software programming, and laboratory analysis, have been conducted in cooperation with *Istituto per i sistemi Agricoli e Forestali del Mediterraneo* (ISAFOM), *Consiglio Nazionale delle Ricerche* (CNR - National Research Council), Perugia, Italy. Finally, LCAs of the four case-specific technical solutions are reported.

Chapter 4 presents studies that combine environmental and economic aspects. Moreover, the following aspects are described: decision-relevant additional costs when substituting, quality grade assessment in horticulture, correlation between selling price of potted plant and its agronomic quality. Finally, additional costs when substituting for peat and plastic pots are calculated and reported.

Chapter 5 presents existing approaches of OR for optimizing the use of resources in agriculture, with focus on blending problems. A blending model is then developed and applied to a case study of a plant nursery located in Pistoia (Italy) by using the four case-specific technical solutions. Objective functions, decision variables, constraints of the model are described. The bi-objective problem of minimizing decision-relevant environmental emissions and decision-relevant additional costs is formulated. Pareto optimal solutions are yielded for different scenarios within the case study.

Chapter 6 presents conclusions of this work, critical aspects, and it introduces robust optimization (for a survey, see Ide & Schöbel, 2016), which deals with uncertain data. The decision problem of this thesis with uncertainties is then investigated (Krüger et al., 2018) by using the approach described in Krüger (2018). The chapter describes at the end further paths for research in horticulture and other sectors.

2 Analysis of peat and plastic use in horticulture

In this chapter, the concept of sustainability is firstly described (Section 2.1), with insights on impacts of the agro-industrial sector, issues related to the use of peat as growth medium and petroleum-based planter containers, cascade utilization, and resource efficiency. Secondly, possible substitutes for peat and plastic containers are described (Section 2.2). Here, focus on compost and bio-based, biodegradable plastics are introduced. These preliminary aspects lay the basis for the evaluation of environmental and economic aspects, which will be analyzed in the next two chapters.

2.1 Environmental sustainability

The concept of *sustainability* follows the principle of the 'triple bottom line' (formalized by Elkington, 1997), where three dimensions of sustainability, i.e., environmental, economic, and social, are taken into account—more aspects can be also included for assessing sustainability (see, e.g., Gibson, 2006; Sianipar et al., 2013). Environmental sustainability, in particular, deals with the global climate change, which is directly correlated to the increment of population and therefore needs of food (and field for cultivating), increment of consumption of natural non-renewable resources, and rising of outdoor air pollution. These aspects were early introduced by Meadows et al. (1974) and, with the passing of the time, has driven the current research in many fields. The Conference hold in Kyoto, Japan (UNFCCC, 1997) presented the most relevant international agreement among State Parties with the dissemination of the Kyoto Protocol, an international treaty that currently include 192 parties worldwide (UNTC, 2005). Shared intents were written towards a systematic way of limiting human activities that are responsible for the release into the atmosphere of GHG emissions (e.g., carbon dioxide, methane, and nitrous oxide). Ten years later, the fourth report of the Intergovernmental Panel on Climate Change (IPCC, 2007) stated that warming of the climate change is unequivocal, due to "observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level". This *global warming* is also driver of other extreme natural reactions, such as hurricanes, floods, droughts, desertification, and alteration of natural habitats that would otherwise be preserved (Solomon et al., 2009). IPCC (2007) stated also that increment in carbon dioxide (CO_2) concentration are mainly due to fossil fuel use, while increment of concentrations of methane (CH_4) and nitrous oxide (N_2O) are primarily due to agricultural activities. Human activities are therefore the most relevant drivers of these environmental changes in many sectors (Rosenzweig et al., 2008; Martin & Saikawa, 2017). Reducing GHG emissions and modifying the demand of fossil resources are drivers for seeking alternative renewable resources (Geldermann et al., 2016a). In horticulture, to determine which resources can be substituted in the supply chain, an overall picture of the impacts should be outlined. This topic is further discussed in the following section.

2.1.1 Impacts of the agro-industrial sector

The agro-industrial and forestry sector contributes 20% of the total anthropogenic GHG emissions (see Figure 2.1), which are increasing at around 1% per year (IPCC, 2014). Changing agricultural practices to reduce GHG emissions in agriculture is nevertheless a challenge, due to economic and implementation limits (Duxbury & Mosier, 1993; Lamb et al., 2016).

An agricultural value chain is a linear concatenation of activities, from livestock/crop production to waste management (Figure 2.2). Other intermediate activities are related to livestock processing (e.g., harvesting, primary and secondary processing), transporting, retailing, and consuming. Here, fundamental drivers for an agricultural value chain are global trends, consumer preferences, costs, sustainability, and product quality. This value chain can be also referred to the horticulture sector, which is a subset of the agricultural ones.

The Italian horticulture sector is one of the most relevant among the agricultural area in Europe (Beccaro et al., 2014). The Pistoia district has been selected due to its relevance in the sector, with about 30% of the national nursery production (Pardossi et al., 2009). Here, about 5200 ha are covered by plant cultivation in nurseries, and over 5500 workers are employed. Horticultural products comprise field-grown plants, potted plants, garden shrubs, broad-leafed and coniferous trees. The potted-plant cultivation of ornamental species, e.g., *photinia*, *osmanthus*, *acer platanoides*, and *cupressus*, exploits a huge quantity of resources (e.g., consumption of diesel for transportation, electrical energy for pumping irrigation water, use of peat as main component of substrate, and use of fertilizers), and it is an important contributor to the GHGs emissions at the local level (Recchia et al., 2013).

A plant nursery has a specific value chain, shown in Figure 2.3. The figure identifies inputs (upper side of the figure), outputs (lower side), and phases that characterize the cultivation activities inside a plant nursery:

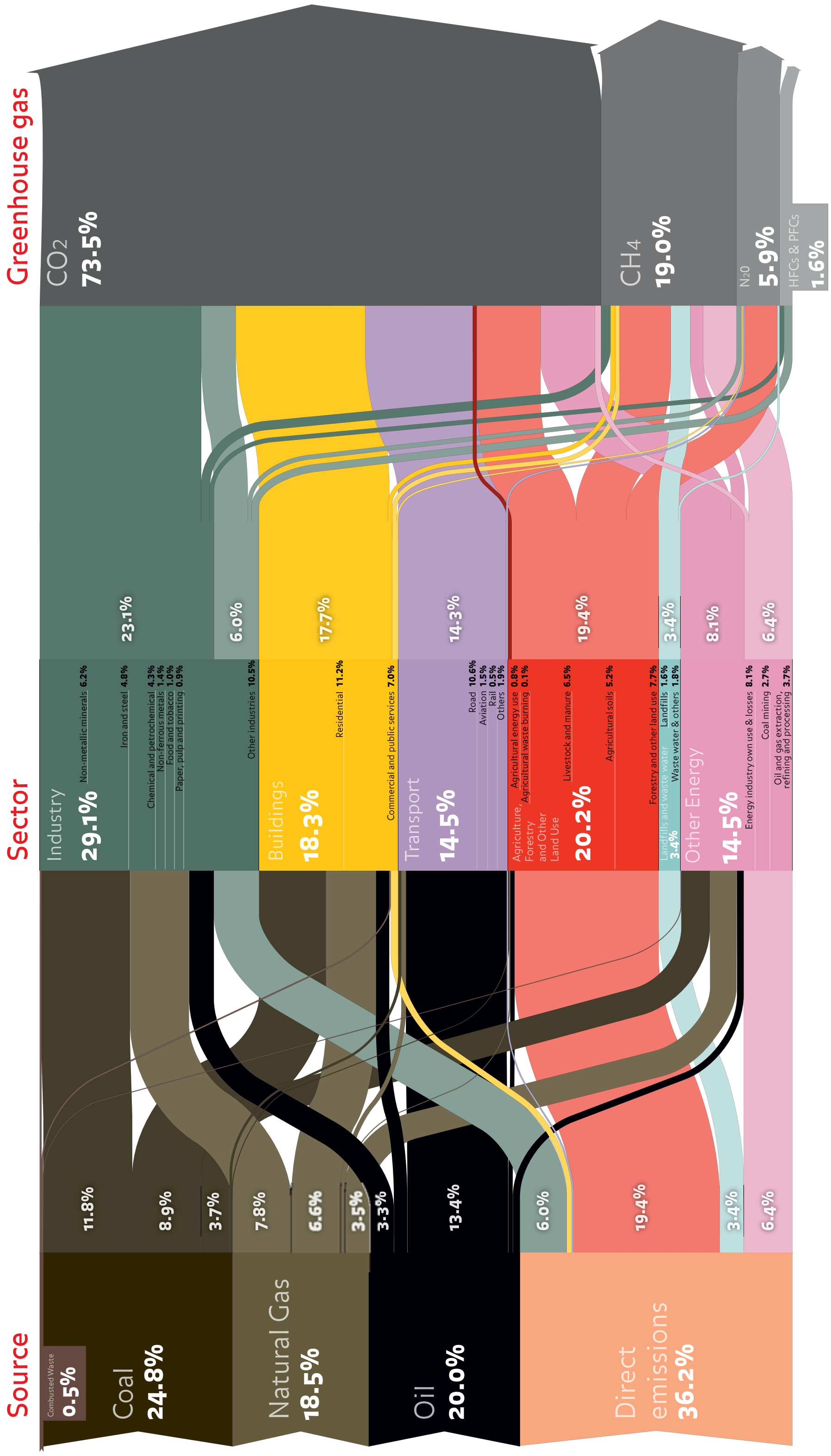

Figure 2.1: World GHG emissions flow chart (2012). Source: ASN Bank & Ecofys 2016 (`www.ecofys.com`), based on International Energy Agency 2014 "CO_2 emissions database" (`www.iea.org`), and Joint Research Centre, European Commission, 2013, Global Emissions EDGAR v4.2 FT2010 (October 2013)

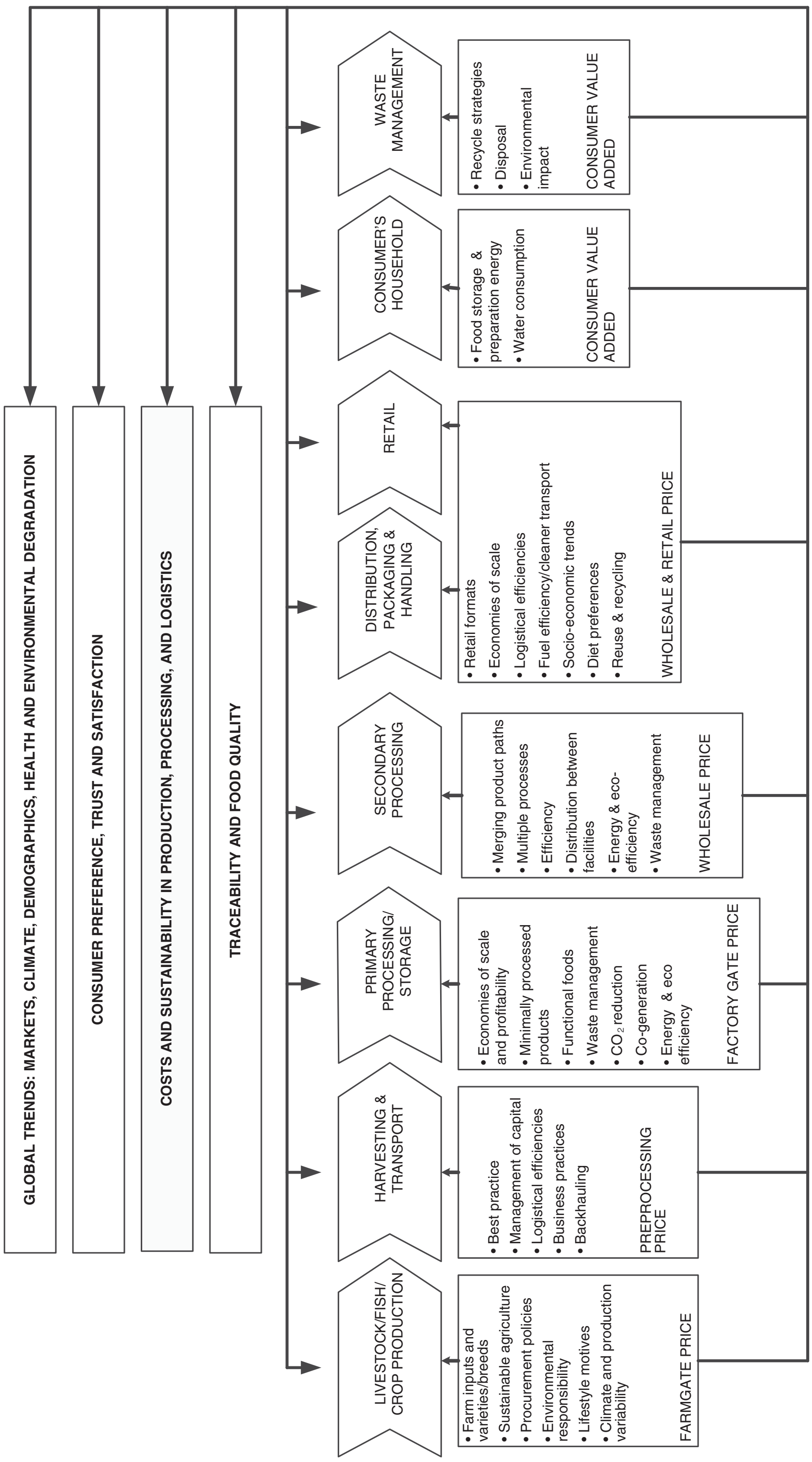

Figure 2.2: General agricultural value chain (Higgins et al., 2010)

- acquiring raw materials required to prepare the substrate for cultivating, mixing the suitable input materials for the specific *species* to prepare the growth substrate—they can be prepared inside the plant nursery or, alternatively, premixed by suppliers and customized for specific applications;
- potting and placing the plant on the ground;
- packaging the potted plant in order to be transported and sold.

Final product of the value chain is an ornamental potted plant cultivated for a season (e.g., one year). This final product is the object of the decision problem of this thesis, described in Chapter 1.

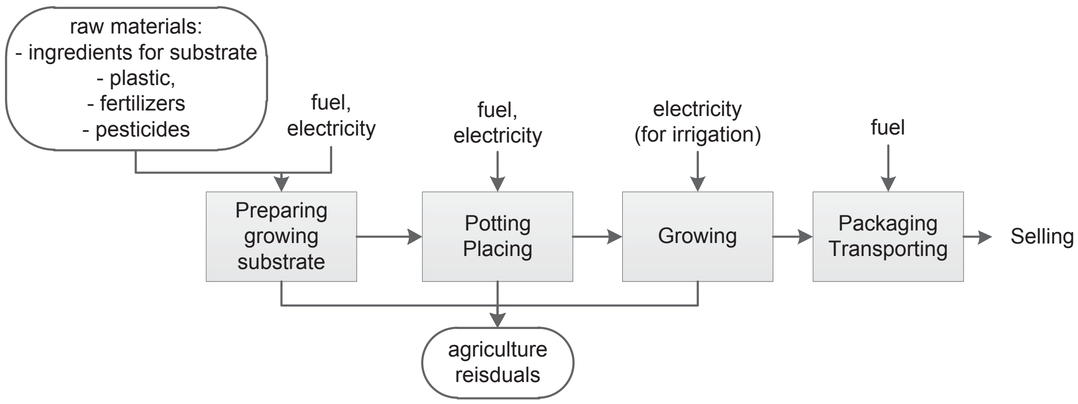

Figure 2.3: Flowchart of a horticultural value chain (for an exemplar plant nursery)

To understand better the implications of substitution of resources used in horticulture, a relevant study (Lazzerini et al., 2014) conducted on the inputs of this value chain is reported here. The study investigated 11 plant nursery located in the Pistoia district (Tuscany region), one of the most important agricultural activity of the district. The study, conducted on potted plant cultivation (pots between 20 and 30 cm of diameter) and field-grown cultivation (plants which are directly grown inside the soil), takes into account six technical parameters for the cultivation of plants: fertilization production, pesticide production, diesel fuel use, electricity use, plastic production, and peat production. The results of the study (Figure 2.4) show that the largest sources of the environmental emissions for potted plant cultivation are related to the use of plastics (e.g., containers, mulching films, packaging plastics) and the use of peat as horticultural medium.

Among the aspects presented so far which raised environmental concern, two are considered in this dissertation due to their relevant contribution to the total environmental emissions of a plant nursery: peat as main constituent of the growth substrate and plastics usage for potting plants.

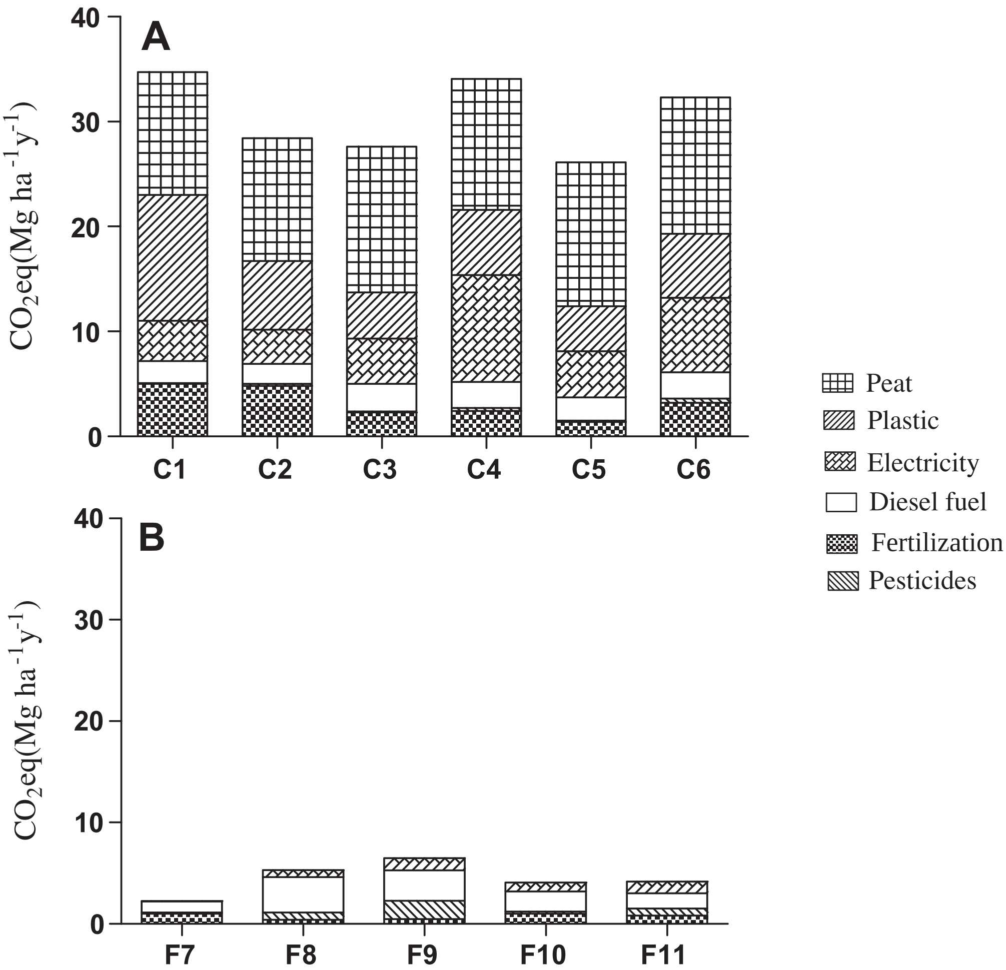

Figure 2.4: Emission factors (t CO_2-eq per hectare per year) of a plant nursery in central Italy.
Notes: The analysis was conducted using the hectare (1 ha) as functional unit of the life cycle assessment for potted plant cultivations in 6 plant nurseries (indicated with "A") and in-field cultivation in 5 plant nurseries (indicated with "B") (Lazzerini et al., 2014)

2.1.2 Peatland and climate protection

Peat is a "sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material" (Joosten & Clarke, 2002), and it accumulates in mires and peatlands. The latter are areas with or without vegetation with a naturally formed peat layer of 30 cm or more on the surface (Strack, 2008, p.17). Peatlands are the most widespread wetland type, cover 4,000,000 km^2 (about 3% of the Earth's land surface), contain 10% of the global freshwater resources, and store one-third of the worldwide soil carbon storage (Gorham, 1991). Over 90% of all peatlands are in temperate and cold belt in the Northern Hemisphere (Maltby & Proctor, 1996). In Europe, peatlands cover more than 282,000 km^2 (about 7% of the worldwide peatland) and it is estimated that around 42% of the total peat usage is used as nursery growth medium for edible plants, ornamental plants, and landscape horticulture (Altmann, 2008). Figure 2.5 presents the share between different horticultural sectors in Europe, with the largest share by floriculture sector (48%), followed by vegetable growing (27%), nursery stock (17%, for potting and in soil use), and other uses.

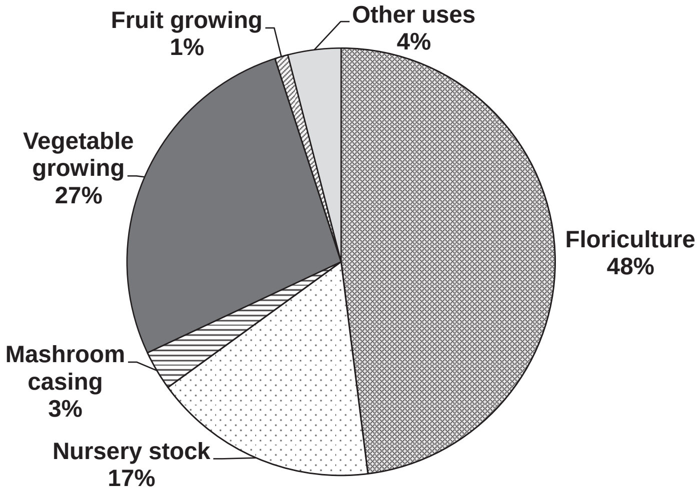

Figure 2.5: Share of peat usage in the growth substrate industry (adapted from Altmann, 2008)

Peat is a very flexible material that can be adapted for most plants, since it is generally low in nutrients, pH, and bulk density. Moreover, it exhibits favorable cation exchange capacity and air-filled porosity characteristics, as well as high structural stability, long-term availability, and uniform properties (Robbins & Evans, 2001). For these reasons, peat is the main growth medium constituent in Europe (Schmilewski, 2013; Reinikainen, 2001).

However, preparing the surface of peatland for harvesting (i.e., removing vegetation and digging ditches), extracting, storing, transporting the peat, and treating the cutaway area have substantial negative impacts on the environment: intensive drainage, water contamination and removal, biodiversity alteration, increment of air pollution, reduction of carbon storage, and increment of atmospheric carbon concentration (Raeymaekers, 1999). Since peat has formed over thousand of years (1 mm per year formation rate, Joosten & Clarke, 2002), and although minimal methane emissions could escape from peatlands, its carbon cycle is assumed isolated from the biological ones. Consequently, peat is considered a non-renewable resource. In Italy, Camporese et al. (2006) described peatland subsidence in the Venice watershed as "irreversible long-term critical issue": drained peat soils, which are mainly related to biochemical aerobic oxidation of the organic matter, cannot be recovered, and plowing has enhanced fossil carbon dioxide release and, subsequently, the sinking rate. In this way, alteration of the soil and mechanical destruction of the peat structure has been performed during the past decades (Camporese et al., 2006).