German Environment Agency
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Critical External Inputs: off-farm compost, off-farm manure and biochar[1]

1 Measure definition

Critical external inputs involve the application of off-farm organic nutrients derived from plant biomass and organic waste materials (plant and animal wastes) for the purpose of soil amendment as well as other environmental applications where carbon is limiting. We consider such inputs as critical because of a) bearing the risk of organic and heavy metal contaminants and b) the risk of high leakage effects regarding climate change mitigation due to excessive import of organic materials from elsewhere. This import could mean a SOC increase at the site where the material is applied, but a depletion in SOC where the material originates from (Gattinger et al. 2012) and no SOC gain in the context of climate change mitigation (Wiesmeier et al. 2019).

Within this scope, only external inputs in the form of solid off-farm manure, compost and biochar (charcoal in simple terms) are discussed, which are traditionally used for soil organic matter management. While manure and compost can be derived via biological decomposition processes, biochar is produced via pyrolysis (heating under limited or no oxygen conditions) respectively (Doble and Kumar 2005; Bihn et al. 2014; Beusch 2021).

To avoid over-complexity, we exclude any liquid or half-liquid waste such as animal slurry and sewage sludge from the assessment here. Further, these two groups of organic wastes often result from industrial structures and are applied because of their N and P provision and not for the purpose of soil organic matter reproduction (Schubert 2017).

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Off-farm compost, off-farm manure and biochar can be applied anywhere in different pedo-climatic conditions, as organic fertilization serves the purpose of nutrient provision and soil organic matter management in farming systems.
- **Suitability in EU/German conditions:** In many European countries quality assurance schemes exist to state the legal compliance regarding residues of heavy metal and organic contaminants. With such quality assurance schemes the conformation with EU organic farming regulation can also be met (e.g. the European Biochar Certificate). There are also restrictions to maximum application amounts per ha and year according to national law and some organic grower association further limit the amount of imported compost and manure (40 kg N equivalents per ha according to some organic growers' regulations).

Fit with NbS definition

As a result of the specialization trend in agricultural and human history since the middle of the 20th century, the exchange of on-farm nutrients between farms with/without livestock and

[1] This factsheet was developed as part of the research project "Naturbasierte Lösungen (NbS) im Klimaschutz: Marktanreize zur Förderung klimaschonender Bodennutzung" (FKZ 3721 42 502 0) and is also published as part of the Annex to the UBA report "Role of soils in climate change mitigation", see www.umweltbundesamt.de/publikationen/Role-of-soils-in-climate-change-mitigation.

between municipalities and their citizens through off-farm manures/composts is one component to close nutrient gaps at farm and even municipality level.

This can be considered as an attempt to mimic traditional, somehow natural food and farming systems. The transportation of manures from livestock dense areas into areas with low livestock density over hundreds of kilometers or even across borders cannot be seen as NbS.

To produce biochar, external energy is required (although Smith et al. (2016) report net energy gains that exceed energy costs) and there are potentially negative effects on biodiversity. Hence, the use of biochar is not fully aligned with the criteria for nature-based solutions as defined in the working definition for this research project as laid out by Reise et al. (2022).

2 Mitigation Potential

2.1 Carbon sequestration

- Application of organic materials can be judged as beneficial for soil carbon sequestration, if no leakage and SOC depletion occurs at the place of origin of the organic materials due to withdrawal of biomass (Wiesmeier et al. 2019). Carbon sequestration in soils is considered to be explicitly linked to a defined area (Olson 2013). Setting thresholds to limit the application amount to be aligned with-site biomass productivity or livestock density to somehow mimic a closed farming system is a means to overcome the leakage problem of off-farm organic materials (Gattinger et al. 2012). Therefore, in this overview we consider only those studies/meta-studies of carbon sequestration rates for application of organic materials where no or only a minor carbon leakage effect can be assumed.
- Regular application of farmyard manure, compost and biochar leads to an increase in SOC compared to mineral fertilization (e.g. Kirchmann et al. 2004; Fliessbach et al. 2007; Diacono and Montemurro 2011; Aguilera et al. 2013; Blanco-Canqui et al. 2019).
- Regular compost applications lead to a sequestration rate of 1.34 t C/ha/year (Aguilera et al. 2013), but these were achieved with application amounts > 3 t C/ha/year. This equals an organic fertilisation intensity of more than two livestock units per ha, which is well above the limit for a closed farming system (Gattinger et al. 2012).
- For the temperate climate, the DOK long-term farming systems trial in Therwil/CH[2] seems to be the only field trial providing accurate data on SOC and non-CO_2 fluxes as influenced by compost, rotted manure, stacked manure, mineral and no fertilisation (Mäder et al. 2002; Skinner et al. 2019). There, compost and manure are applied according to a fertilisation intensity of 0.7 and 1.4 livestock units per ha, which can be considered free of any carbon leakage effect (see above). It turned out, that only at 1.4 organic fertilisation intensity carbon sequestration can be achieved but at rates well below 0.2 t C/ha/year (Krause et al. in prep).
- Not much is known regarding actual SOC sequestration rates or changes in SOC stocks due to biochar application in Germany or within the EU. However, the addition of biochar to soils of an experimental field site in Germany was reported to slow down SOC decomposition rates

[2] Established in 1978; www.fibl.org/en/themes/projectdatabase/projectitem/project/404.

resulting in SOC decomposition of less than 0.3% per year (Kuzyakov et al., 2014). A field study in the US revealed that soil carbon increased by twice the amount of biochar carbon applied after 6 years. The corresponding sequestration rate due to biochar application is 1.97 t C/ha/year (Blanco-Canqui et al. 2019). The total increase in C stocks in the biochar-amended plots was nearly twice (14.1 t SOC/ha) the amount of C added with biochar 6 years earlier (7.25 t C/ha biochar), suggesting a negative priming effect of biochar on formation and/or mineralization (Blanco-Canqui et al. 2019). Similar phenomenon was reported from Brazil with an increase of soil carbon stocks by 2.35 t C/ha/year with an application rate of 0.4 t biochar/ha/year in sugarcane field sites (Lefebvre et al. 2020).

2.2 Total climate impact

The total climate impact of off-farm inputs will depend on the impact that these inputs have at farm level, as well as the additional emissions associated with the transport of off-farm inputs, leakage to other land, and substitution of previous use. Such assessments are not available, likely also due to lack of available synthesized information on patterns of transport and the amounts of off-farm inputs applied.

- The use of manure or compost can potentially reduce GHG emissions by avoiding uncontrolled storage of manure (Petersen et al., 2013). Composting systems such as `turned composting´ can potentially reduce GHGs emissions with reduction in N_2O by 50%, and CH_4 by 71% as documented from a global meta-analysis (Pardo et al., 2015). However, research on the impact of compost and manure storage and processing on total GHG emissions is very limited, with the Pardo et al (2015) meta-analysis based only on 11 original research papers.

- At the same time, the application of compost and manure in closed farming systems often leads to N_2O emissions from soils which are higher in CO_2 equivalents than the carbon sequestration effect (Gattinger et al. 2012; Skinner et al. 2014; Skinner et al. 2019; Wiesmeier et al. 2020). We are not aware of life cycle assessment (LCA) analyses which are based on measured GHG emission data from field experiments on compost and/or manure use. Nemecek et al. (2011) conducted a LCA on the various farming systems on the DOK trial using default values as emission factors. It turned out that the two systems with solely organic fertilization (compost and rotted manure) showed significantly lower carbon footprint per ha and per dry matter product than the system with synthetic fertilizer and stacked farmyard manure.

- Compost particularly green waste compost (wood clippings and other plant debris from public and private gardens) can offer a substantial contribution to replace peat as a growing substrate in horticulture. In the German federal government's climate protection plan for 2050 and in the coalition agreement from 2018, peat use in the horticultural sector is mentioned as a cause of greenhouse gas emissions and it is stated that the use of peat as a growing medium should be significantly reduced. In Germany, around 8 million cbm of peat are processed annually as a substrate for domestic horticulture and export (Thuenen Institut 2022). The extraction and use of peat as a plant substrate causes greenhouse gas emissions due to the decomposition of the peat. According to climate reporting data, emissions of more than 2 million t CO_2 equivalents are generated in Germany from this activity (Thuenen

Institut 2022). Several projects under the auspices of FNR and BLE are on-going to investigate and develop peat replacement products. Bundesgütegemeinschaft Kompost (BGK 2021) estimates, that the compost demand for potting mixes will rise from 1 million cbm in 2017 to 5 million cbm in 2050. Covering GHGs like CO_2, CH_4, and N_2O, Teichmann et al. (2014) found that biochar soil incorporation has a GHG mitigation potential of 2.8 - 10.2 Mt CO_2-eq. by 2030 and 2.9 - 10.6 Mt CO_2-eq. by 2050 in Germany, if costs are not considered. This represents 0.4 - 1.5% and 0.3 - 1.1% respectively of Germany´s GHG reduction targets by 2030 and 2050.

- In a synthesis on 20 years of biochar reduced non-CO_2 greenhouse gas emissions (N_2O and CH_4) from soil by 12% - 50% (Joseph et al. 2021). Although these potentials were often achieved with high biochar application amounts, comparable GHG mitigation potentials were not reported for compost and manure. The data on N_2O and CH_4 effects of compost and manure are not (yet) available.

2.3 Limitation on the mitigation potential

Apart from the restrictions when considering off-farm resources for soil carbon there are further limitations to list:

- Despite positive effects of GHG emissions, turned and forced aerated composting systems may cause an increase in NH_3 emissions by 54% - 121% (Pardo et al. 2015). Mismanagement of the application rate, method and timing can also lead to N_2O emissions, and should be optimized to avoid these effects (Petersen et al. 2013).

- The availability of excess feedstock biomass is limited to produce soil inputs such as biochar, and this was reported to lead to a lower “sustainable” global potential of 0.5-2.0 $GtCO_2$ per year with negative emissions (Fuss et al. 2018). Also, the experience with large-scale production and the use of biochar is missing and feasibility, long-term mitigation potentials, side-effects and trade-offs remain largely unknown (Fuss et al. 2018; Jian et al. 2019).

- Effects of manure and compost on SOC sequestration may vary depending on the manure application rate, initial SOC content, land use, management system, etc (Maillard and Angers, 2014). The precise impacts of biochar on field soils is also uncertain (Smith 2016; Tammeorg et al. 2016) as its use has not been considerably demonstrated beyond laboratory research settings (Griscom et al. 2017). Long term field trials are thus lacking, and few documented ones contradict with lab studies (Vijay et al. 2021). A broader lifecycle assessment is thus necessary to determine the mitigation effect of biochar as an exogenous carbon input to soils.

- When considering benefits to soil, manure quality is more important than manure quantity (Köninger et al. 2021), thus only application of manure that is free of contaminants / pollutants will be beneficial to soil biodiversity.

- The quality of animal manure applied and hereby, benefits to plant depends on the diet of the animals (Petersen et al. 2013). Similarly, the carbon conversion efficiency of biomass to biochar is highly dependent on the nature of the feedstock material (Lehmann et al. 2006).

- Surface application of biochar carries the risk of reducing the albedo effect of agricultural croplands / landscapes. The addition of high temperature-produced biochar to soils may enhance the decomposition of SOC (Budai et al. 2016). The addition of dark colour biochar may reduce the magnitude of solar radiation reflected to space (albedo) and this can increase soil temperature (Smith 2015), which in turn might lead to SOC decomposition and losses and increase CO_2 emissions. For example, 30 - 60 t ha^{-1} biochar application to experimental field soils in Italy decreased surface albedo by up to 80% (Genesio et al. 2012). Similar albedo reduction with 30 - 32 Mg ha^{-1} of biochar has been reported for arable field sites in Germany, leading to reduction of climate change mitigation potential by 13 - 22% (Meyer et al. 2012). The extent to which this would negate the positive climate impact of biochar is unclear as we do not have studies that address these trade-offs. This risk is reduced when biochar is incorporated in soils.

3 Adaptation and co-benefits

- **Waste management:** Adopting off-farm manure, compost and biochar as soil amendment enable improved waste management (Paul et al. 2001; Doble and Kumar 2005; Roberts et al. 2010) and thus can contribute to circularity in food and farming systems (Van Zanten et al. 2019).
- **Improved soil structure and soil health:** There is vast body of literature indicating the beneficial effect on improved soil structure and soil health as influenced by compost and manure (e.g. Diacono and Montemurro 2011) as well as biochar (e.g. Joseph et al. 2021).
- **Soil biodiversity:** There is vast body of literature indicating the beneficial effect on soil biodiversity as influenced by compost and manure (e.g., Diacono and Montemurro 2011; Hartmann et al. 2015) as well as biochar (e.g. Krause et al. 2018; Joseph et al. 2021).
- **Yield:** A vast body of literature exists to underline the fertilization and soil improving effects of manure and compost resulting in higher crop yields as compared to unfertilized or mineral fertilized treatments (e.g. Diacono and Montemurro 2011). For biochar, increase in agricultural productivity can be particularly beneficial in degraded or low fertility soils (Lehmann et al. 2006; Woolf et al. 2010) causing increase in plant growth and leaf cell expansion, most likely due to fertilisation effect and to the up-regulation of relevant plant hormones (Viger et al. 2015).
- **Reduced use of nitrogen** fertilizers**:** The use of external inputs such as manure, compost and biochar reduce the need for synthetic fertilizers (Borchard et al. 2019; EEA 2021).
- The application of biochar to soil can stabilize soil organic matter due to accelerated formation of microaggregates by organo-mineral interactions as described for a field site in Australia (Weng et al. 2017). It also improves soil porosity and decrease bulk soil density (Blanco-Canqui et al. 2017). In addition to effects on soil physical properties, adding of biochar to soils offer benefits to soil chemistry, e.g., can lead to a balance in soil pH, salinity/sodicity, and cation exchange capacity of soils (Vijay et al. 2021).

- **Improved water holding capacity, reduced erosion:** Increasing soil organic matter inputs to soils may increase water-stable large aggregates and this can improve water holding capacity and protect against soil erosion (Wortmann and Shapiro 2007).

4 Trade offs

- **Contaminants and foreign matter:** With the systematic accreditation of commercial composting plants with the RAL Gütesiegel[3], heavy metal and other pollutants could be reduced to an environmentally acceptable minimum level over decades. The same applies for the European Biochar Certificate in the case of biochar application. However, there is the issue of foreign matter, predominantly plastic in municipal compost particularly biowaste compost, which is produced by separate collection of household and kitchen waste. Despite the existence of various legal frameworks, the plastic content of representative composts varies between 0.05 to 1.36 g per kg compost (Braun et al. 2021). Upscaling these loads to common recommendations in composting practice, which range from 7 to 35 t compost ha^{-1}, suggest that compost application to agricultural fields goes along with plastic loads between 0.34 to 47.53 kg plastic ha^{-1} $year^{-1}$ (Braun et al. 2021).
- **Soil biodiversity:** In principle one could assume that the use of compost or manure increases soil biodiversity in comparison to solely mineral fertilisation. However, the impact on soils will depend on the quantity and the quality of these inputs, as shown in the previous bullet point. In terms of biochar, its effects on soil biodiversity is also dependent the feedstock and the pyrolysis temperature (Budai et al. 2016; Vijay et al. 2021) as microbial biomass varies with different types and amount of biochar used (Jiang et al. 2016). This missing knowledge gaps stress the need for further investigation on its potential benefits and trade-offs.
- **Soil compaction:** As composts and farmyard manure are usually low in plant nutrients, their application on croplands goes along with high wheel loads on soil. Among harmful soil compaction by vehicular traffic, manure and compost application have the highest impact (Thorsoe et al. 2019). Thus, strategies reducing the frequency of broadcast application techniques are needed. One approach might be the row application of compost along with potato planting as invented by University of Kassel.[4] The same holds true for broadcast biochar applications. For instance, combining deep soil loosening with biochar application beneath the main rooting zones of crops is supposed to i) reduce application amounts and wheel loads, ii) promote plant growth and carbon storage and iii) enhance albedo effects as opposed to broadcast application.[5]
- **Particular matter:** The application of biochar to soils can lead to an increased emission of particulate matter as firstly biochar tends to absorb fine particles and secondly, soil

[3] www.ral-guetezeichen.de.

[4] https://univideo.uni-kassel.de/category/video/-KOMPOST-in-Kartoffeln-Technik-zur-Reihenapplikation/8aba5a42cd03654da02095b9e159d0e9/1.

[5] A. Gattinger, personnel communication, see also www.humuvation.de.

properties can induce abrasion of larger biochar particles. These activities can also potentially lower its mitigation potential and increase air pollution (Ravi et al. 2015).

- **Nutrient availability:** Manure or compost application may increase the risk of phosphorus runoff especially within the first few days after application, limiting phosphorus availability to plants although increased macro-aggregation may afterwards protect against subsequent phosphorus losses (Wortmann and Shapiro 2007). With biochar, reports on its effect on plant defense system are uncertain, with studies reporting both positive and negative outcomes (Meller et al. 2012; Viger et al. 2016).

5 Implementation challenges

Sustainable utilisation of off-farm manure, compost and biochar requires schemes on quality control and environmental compliance. Several regulations are in place already, but orientation along the EU organic regulation for these off-farm inputs would bring highest environmental standards and help to consider these practices as means towards natural based solutions. Moreover, to ensure that the positive climate impact is not reduced or negated by long distance transport and to address the challenges of having limited availability of biomass and competing demands on it, strategic planning and a landscape level framework is needed for how to handle organic waste and biomass flows and prioritize their use at a landscape level. Uncertainties associated with biochar's impact on climate and biodiversity require that precautionary principles are applied and this option is promoted only once and if its positive impact within the EU context is backed with clear evidence.

In terms of replacement of peat in growing media, this option has a high potential. A ban on its use or a strong reduction would reduce pressure on peatlands and have a positive climate impact. The phasing out of its use could be achieved by gradually decreasing the share of peat that is allowed in potting mixes, for example some organic grower associations already limit peat use by setting a maximum value of 70% peat in potting mixes for organic agriculture and horticulture.

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