Impact of specialised sugar beet crop rotations on soil fertility parameters and on yield and yield stability of sugar beet

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List of abbreviations

a	Year
AC	Air capacity
Alf	Alfalfa, *Medicago* ssp.
aminoN	α-amino nitrogen
CC	Cropping concentration
CI	Cropping interval
CR	Crop rotation
DWD	Deutscher Wetterdienst
FC	Field capacity
GM	Grain maize, *Zea mays* L.
HU	Humus Unit
k_S	Saturated hydraulic conductivity
MBC	Microbial biomass carbon
Mu	Mustard, *Sinapis alba* L.
Pot	Potato, *Solanum tuberosum* L.
RY	Root yield
SB	Sugar beet, *Beta vulgaris* L.
SC	Sugar content
SCI	Soil Compaction Index
SOM	Soil organic matter
SOC	Soil organic carbon (= TOC)
SM	Silage maize, *Zea mays* L.
SML	Standard molasses loss
SWC	Soil water content
TOC	Total organic carbon (= SOC)
TC	Total carbon
TIC	Total inorganic carbon
vol%	Percentage by volume
WSC	White sugar content
WSY	White sugar yield
WW	Winter wheat, *Triticum aestivum* L.
σ_P	Precompression stress
σ_Z	Major principal stress
% FC	Percentage of field capacity

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I Prologue

1 Introduction

Feeding a growing world population sustainably is the challenge of current and future generations. In this context, Alexandratos and Bruinsma (2012) updated the FAO's 2006 study on the prospects for the global agriculture and food situation in the year 2050 (FAO, 2006a), extending it by considering the likely availability of factors of production (land, water, fertilizers). This results in the following key points: (i) By 2050, the world population will have grown by approximately 2.25 billion to around 9.15 billion people. (ii) The associated growth in the demand for food will necessitate production increases of approximately 45 % for cereals, 76 % for meat, 75 % for sugar and 89 % for oilseed crops (compared to 2005/2007). (iii) Of this increase in production, around 10 % will have to be accounted for by expanding agricultural land, around 10 % by extending harvested areas (shorter fallow periods, multiple harvests each year) and around 80 % by increasing crop yield.

Over the last 50 years, crop-specific yield achieved in practice have risen by between 45 % (sugar cane, *Saccharum officinarum* L.) and 235 % (oilseed rape, *Brassica napus* L.); in the case of sugar beet (*Beta vulgaris* L.), yield increase of approximately 110 % has been seen (Hoffmann and Loel, 2015). Apart from breeding, this increase in yield is the result of an intensification of agriculture through higher input and improved agronomic practices. However, this has been and still is associated with environmental impacts, and questions have been raised about the sustainability of this intensification (Matson et al., 1997). Modern, sustainable production methods must ensure that the genetic yield potential of crops is fully utilised in a manner that protects both resources and the environment. Nutrient and water use efficiency as well as disease, pest and weed control need to be improved by using suitable varieties and adapted agronomic practices (Tilman et al., 2002). The planning of crop rotation systems plays a major role in this context. It is important to use ecosystem services within the crop rotation to increase soil fertility and reduce harmful environmental impacts (Kay, 1990; Matson et al., 1997; Tilman et al., 2002; Petersen and Snapp, 2015). In the past, however, the increased availability of industrial nitrogen fertilizers and synthetic chemical plant protection products has led to a substantial simplification of crop rotations (Ball et al., 2005), although a favourable position within crop rotation, with reduced applications of plant protection products and fertilizers, can increase yield and yield stability (Coulter et al., 2011), and in turn improve energy efficiency (input/output ratio) as well (Jacobs et al., 2016b). In addition, extending crop rotations by adding forage crops – for example when cultivating grain maize (*Zea mays* L.) – can have a favourable impact on soil quality compared to cultivating grain maize in monoculture or short grain maize-soybean (*Glycine max* (L.) Merr.) crop rotations (Karlen et al., 2006). Extended crop rotations are therefore advantageous in terms of energy and ecological aspects. However, an increase in the intensity or efficiency of land use is essential in order to meet the growing demand for food and renewable resources (Bennett et al., 2012), and the concentrated cultivation of crops with a high potential for biomass formation within the crop rotation can result in more efficient land use, even if yield is lower, than cultivating crops in extended crop rotations (Jacobs et al., 2016b). In keeping with the principle of sustainable intensification, it is necessary to increase, in an environmentally friendly manner, the proportion of crops within crop rotations which produce the largest amounts of biomass and/or food, and at the same time to take appropriate steps towards reducing yield losses which are caused by a less favourable crop rotation position (Bennett et al., 2012).

Compared to most crops typically cultivated in Central Europe, sugar beet is characterised by a high potential for biomass formation (Hoffmann and Stockfisch, 2010), a favourable energy balance and high land use efficiency (Tzilivakis et al., 2005; Reineke et al., 2013). In the European Union, some 1.3 million ha of sugar beets were grown, and 14.9 million t of white sugar produced in the 2015/16 agricultural year (WVZ, 2016a). In Germany, the total sugar beet cultivation area averaged 0.3 million ha across the agricultural years from 2013/14 until 2015/16, with an average of 3.6 million t of white sugar produced each year (WVZ, 2016b). In addition to utilising sugar beets for producing sugar for food, there are also benefits to using this crop as a renewable resource and approximately 36 % of the German bioethanol production in 2015 was produced using sugar beets (BDBe, 2016).

Relative to the total arable land in Germany, at 3.0 % the cultivation of sugar beet is not particularly widespread, although the area cultivated can be in excess of 10 % regionally (WVZ, 2016b). For sugar beet, short crop rotations are not customary at present due to a high yield loss if cultivated in narrow crop rotation (Wiesner, 1977). In Germany's typical cultivation regions, under current production conditions sugar beet is primarily grown with a cropping interval of two to four years (Märländer et al., 2003; Graber and

Risser, 2013) in crop rotations with winter cereals (Märländer et al., 2003; Buhre et al., 2014). The abolition of the European quota system for sugar in 2017 (European Union, 2013) could however lead to increased interest in specialised, concentrated sugar beet crop rotations. According to estimates, EU sugar production may consequently rise by 4 %, with the biggest increases in Denmark, Germany, the United Kingdom and Romania (Burrell et al., 2014). Similarly to the consequences of the sugar market reform in 2006, which saw a number of countries cease sugar beet cultivation altogether (Ireland, Latvia, Slovenia, Bulgaria, Portugal) or at least scale back their production (Greece, Spain, Italy), sugar beet production will continue to become more concentrated in the most suitable growing regions (Bichara Rocha, 2014), which include the areas in Germany where sugar beet is typically cultivated. The increased demand for sugar beets as a substrate for biogas plants may in practice also lead to increased interest in specialised sugar beet crop rotations, since sugar beet achieves similar dry matter and methane yield per hectare to those of silage maize (Brauer-Siebrecht et al., 2016) and it has been debated as one alternative to extend short silage maize crop rotations (Jacobs et al., 2014).

Specialised crop rotations with increasing sugar beet cropping concentrations may provide one way of raising land productivity. However, impacts on the environment and yield need to be quantified in order to ensure that any increase in productivity is sustainable. Against this backdrop, this thesis will focus on impacts on soil fertility (as an important agri-environmental indicator) and on sugar beet yield and yield stability. The following chapters summarise the current state of knowledge and specify the need for further research.

2 Impact of sugar beet cultivation on soil fertility parameters

The soil’s suitability to serve as a habitat for plants is described as soil fertility (Scheffer et al., 2002). Soil fertility is characterised by all of the biological, chemical and physical soil properties that affect vegetation. Depending on the specific site, these properties are predetermined within specific limits by the geological (texture, mineral composition, parent rock etc.) and geographical conditions (altitude, climate, exposure etc.). Anthropogenic use, however, modifies the soil properties within the predetermined limits. The parameters which substantially determine soil fertility, and which are influenced by the type of crop grown, include the soil organic matter or soil organic carbon content (Havlin et al., 1990; Campbell et al., 1991; Janzen et al., 1997; Reeves, 1997; Carter, 2002; Körschens, 2010; Lal, 2011; Fageria, 2012; Triberti et al., 2016) as well as the soil's structural and physical properties (Topp et al., 1997; Miglierina et al., 2000; Karlen et al., 2006; Mueller et al., 2010; Liesch et al., 2011).

2.1 Impact of sugar beet cultivation on soil organic matter content

In simplified terms, soil organic matter content can be divided into an inert fraction, which is not determined by the cultivation process and changes only over very long periods, and a labile fraction which can be influenced by the cultivation process (Janzen et al., 1997; Körschens et al., 1998). Depending on the methodology used, different components of the convertible fraction are described; these will not be discussed in detail here.

The soil organic matter content is conventionally calculated using the soil organic carbon content and the factor 1.724 (= C content of peat, Johnston et al., 2009). Changes to the soil organic matter content result from divergence between the supply of organic carbon and carbon losses through decomposition (Janzen et al., 1997). The crop cultivated influences these dynamics, and in the long term the soil organic matter content, through (i) varying quality and quantity of the organic matter formed during vegetation which remain on the field after harvest (crop and root residues), (ii) tillage intensity and (iii) the length of the vegetation period (Körschens, 1988).

Klimanek (1987) compiled results from the literature on the crop and root residues of different crops. According to the studies evaluated, sugar beets leave an average of 1.5 t ha^{-1} of crop and root residues (dry matter, no leaves). In comparison, winter wheat (*Triticum aestivum* L.) leaves 3.6 t ha^{-1} (without straw), and silage maize 3.8 t ha^{-1}. These higher levels of crop and root residues from winter wheat and silage maize are primarily due to higher root residues. According to a review of the literature by Bolinder et al. (2015), sugar beets leave between 0.28 and 0.40 t ha^{-1} of fine root residues at harvest. Only a few studies have considered the amount of fine roots which are produced during vegetation and already converted. In this context, van Noordwijk et al. (1994) calculated lower production of fine roots for sugar beets (1.15 t ha^{-1}) compared to winter wheat (1.76 to 1.96 t ha^{-1}).

When taking into account the above-ground residues leaves and crowns, sugar beets can leave behind similar amounts of carbon to winter wheat stubble and straw (Sleutel et al., 2007; Koga and Tsuji, 2009). However, the net mineralisation of the organically bound nitrogen of sugar beet leaves is higher than that of wheat (Bending et al., 2002), and therefore a lesser contribution to soil organic matter is attributed to sugar beet leaves (humus reproduction coefficient,VDLUFA, 2014). This is also the reason Triberti et al. (2016) believe to be responsible for the lower soil organic carbon stock (0-40 cm) of a sugar beet-winter wheat crop rotation compared to a winter wheat-winter wheat crop rotation.

Due to the elaborate methodology for determining crop and root residues and the correspondingly low number of published measurements, modelling approaches have been developed to calculate crop-specific carbon inputs. Assuming that using the same management methods over many years will result in a balance in soil organic carbon levels on soil monitoring areas and field trials, it is possible to apply the Rothamsted Carbon Model (Coleman et al., 1997) inversely in order to calculate the crop-specific carbon inputs required to establish such a balance. For soil monitoring areas in France, Meersmans et al. (2013) calculated a carbon supply through the cultivation of sugar beet amounting to 2.79 t C ha^{-1} a^{-1}, which was a similar level to that of winter wheat (2.51 t C ha^{-1} a^{-1}). For the static fertilization trial in Bad Lauchstädt, Ludwig et al. (2007) calculated a carbon supply through the cultivation of sugar beet of 0.91 t C ha^{-1} a^{-1}. By comparison, winter wheat added 2.43 t C ha^{-1} a^{-1} to the soil (removal of beet leaves and wheat straw). For this study, the best adaptation of the model came from integrating literature data from Klimanek (1987) and Klimanek (1997) and calculating the carbon supply through rhizodeposition with a crop-specific factor (35 % of crop and root residues for sugar beet, 50 % for winter wheat). Van Wesemael et al. (2010) also used this factor, although they calculated the crop-specific carbon supply depending on yield following Franko (1997). For sugar beets, this resulted in a carbon supply of 0.91 t C ha^{-1} a^{-1} (cereal: 2.44 t C ha^{-1} a^{-1}). The differences in carbon supply seen in individual studies are due in part to differing model assumptions (yield-dependent, literature values etc.) but also to different experimental and site conditions (removal of sugar beet leaves, soil tillage).

In addition to crop and root residues, soil tillage has a significant influence on the amount of carbon input and the soil organic matter content. Tillage affects soil organic matter dynamics by changing the soil climate, incorporating organic matter and above-ground plant residues into the soil and periodically disturbing the soil structure (Balesdent et al., 2000). In crop rotations with sugar beet and cereals, Andruschkewitsch et al. (2013) found lower soil organic carbon contents following conventional tillage with the plough, particularly in the topsoil (0-5 cm reference soil depth), than for less intensive tillage such as mulch tillage and no tillage. Based on a reference soil depth of 0-40 cm, smaller soil organic carbon stocks were still found under conventional tillage compared to mulch tillage, whereas the no-tillage variant displayed similarly high soil organic carbon stock, which was presumably due to low yield of sugar beet and winter wheat. Reducing tillage intensity can therefore also have an adverse effect. In the past, the cultivation of sugar beet required highly intensive tillage. Standard sugar beet cultivation practices included stubble cultivation with a parer following a preceding cereal crop, primary soil tillage with a plough in the autumn, multiple working steps for seedbed preparation, and mechanical weed control through repeated hoeing (Lüdecke, 1953; Lorenz et al., 1974). It was also common practice to remove sugar beet leaves. In the older literature, lower soil organic carbon contents are often reported in crop rotation variants with sugar beets or in sugar beet monoculture (Beck, 1975; Steinbrenner and Smukalski, 1984; Wicke and Matthies, 1990; Krauss et al., 1997). Apart from lower amounts of crop and root residues, these values would also have been caused by higher tillage intensity. The current humus balance coefficients (VDLUFA, 2014) are based on data from 30 long-term field trials compiled by Asmus and Herrmann (1977) and Körschens (1988). Based on this data, sugar beet is associated with the lowest humus reproduction coefficient, so the highest carbon loss. This classification is partly due to the sugar beet cultivation practices described above, which do not represent the current practices.

In Germany, current cultivation methods are characterised by significantly lower tillage intensity. As such, approximately 50 % of sugar beet acreage is cultivated without using a plough (Buhre et al., 2014) and only a small proportion of the overall area is hoed (Märländer et al., 2003). However, there is still a lack of accurate evidence on the impact of reduced tillage on the humus reproduction coefficients of different crop types, and further research is also required into the influence of the increased yield level (Körschens et al., 2005; VDLUFA, 2014). In the context of increasing yield, Wiesmeier et al. (2014) calculated increasing annual carbon supplies of various crops for the period from 1951 to 2010. Compared to winter wheat (112 % increase) this increase was relatively low for sugar beet (55 % increase).

2.2 Impact of sugar beet cultivation on soil structure

The crop cultivated can affect the soil structure through a variety of factors, which should not be considered independently but can influence each other mutually. These factors include:

- Root system and root penetration behaviour (Chan and Heenan, 1996; Angers and Caron, 1998; Ball et al., 2005).
- The supply of organic material, e.g. from crop and root residues (Ball et al., 2005; Blanco-Canqui and Lal, 2009).
- Developing of cracks, especially on clay soils, through processes of swelling and shrinkage by modifying the soil water regime (Angers and Caron, 1998).
- The promotion of soil fauna, which itself affects soil structure (Lee and Foster, 1991), through the duration of the soil rest period (Vetter and Lichtenstein, 1968).
- Aggregate stabilisation through the secretion of root exudates and as a source of carbon for microorganisms (Angers and Caron, 1998), which promote aggregate formation (Anderson, 1991).
- The intensity and frequency of tillage operations (Kay, 1990).
- The mechanical stresses associated with driving over the soil with agricultural machinery (Nawaz et al., 2013; Rücknagel et al., 2015).

In the scientific literature, however, only a few studies have been published on the impact of sugar beet cultivation on soil structure. Głąb et al. (2013) for example found evidence of higher macropore volumes (soil depth 0-20 cm) after sugar beet as a preceding crop compared to triticale (*Triticosecale* Wittm.) as a preceding crop, which they partially attribute to the manure application before sugar beet sowing. Deumelandt et al. (2010) observed no differences in soil structure (soil depth 8-38 cm) with increasing cropping concentration of sugar beet in the crop rotation. In the topsoil, this was probably due to a homogenisation of the soil structure as a result of turning the soil. In the investigations by Jacobs et al. (2014), silage maize and sugar beet monocultures displayed lower air capacity and saturated hydraulic conductivity as well as higher dry bulk densities in the upper topsoil (soil depth 8-12 cm) than winter wheat monoculture. The less favourable soil structure detected beneath sugar beet and silage maize was attributed to a less extensive root system at the time of sampling, a smaller amount of crop and root residues and a higher risk of soil compaction when sowing and harvesting.

Boizard et al. (2002) and Capowiez et al. (2009) found a less favourable soil structure, in the form of higher proportions of compacted zones in the soil (soil depth 0-80 cm) and lower water infiltration (below 2 cm soil depth), when integrating sugar beet and silage maize into the crop rotation, particularly if the sugar beet and silage maize were harvested when soil water contents were higher.

In particular, the studies by Boizard et al. (2002) and Capowiez et al. (2009) indicate that the harvest operations of sugar beets may potentially be associated with a negative impact on soil structure, and, under certain conditions, possibly culminating in harmful soil compaction. High wheel loads, frequent passes over the soil, high soil water contents at the time of driving over the soil and a high tyre inflation pressure promote soil compaction when using agricultural machinery (Canillas and Salokhe, 2001; Rücknagel et al., 2012). When fully loaded, modern six-row self-propelled sugar beet harvesters can weigh up to 65 t in the case of three-axle machines, and 45 t with two axles, resulting in axle loads of around 22.5 t and wheel loads of around 11 t (Brantner et al., 2014). In field trials involving standard tyres (inflation pressure of 180 kPa to 300 kPa), wheel loads of 8 t to 11 t, single passes over the soil and soil water contents of > 70 % of field capacity, soil compaction has generally been shown to occur in the topsoil (up to 30 cm soil depth) as a result of driving over the soil with sugar beet harvesters (Arvidsson, 2001; Gysi, 2001; Schäfer-Landefeld et al., 2004; Yavuzcan et al., 2005; Heuer et al., 2008; Koch et al., 2008). Soil compactions in this depth can be loosened again by routinely performing primary tillage. However, driving over the soil multiple times – which is often the case on agricultural headlands – can impair soil structure down to the subsoil (below 30 cm soil depth, Arvidsson, 2001; Koch et al., 2008). In this area, soil compaction is not reversed by routine primary tillage and is usually persistent (Alakukku, 1996). It is therefore important to avoid soil compaction in the subsoil.

In order to assess and compare the effects of cultivating crops by driving over the soil with agricultural machinery, it is necessary to take into account the proportion of wheeled area, the frequency of wheeling and the associated contact pressures for each cultivation method. On this basis, and assuming half-full hoppers, Zapf and Kotzki (1997) calculated the soil compaction risk for typical Bavarian crop rotations. Compared to winter cereals and winter oilseed rape, the cultivation of sugar beets resulted in the highest proportions of the area subjected to a wheel load of > 4 t, with a 66 % lower proportion of non-wheeled area. The study by Zapf and Kotzki (1997) did not consider the operation specific soil water content. This is however necessary in order to assess the soil compaction risk of the individual methods of cultivation.

3 Impact of crop rotation on yield and yield stability of sugar beet

Sugar beets are ascribed a high yield loss when cultivated in short crop rotation or monoculture. In this regard, Wiesner (1977) evaluated 31 studies with a total of > 200 years of investigation into the impact on yield of increased cropping concentrations of sugar beets. For these studies, the amount of yield loss with increasing cropping concentration depended on the previous cultivation methods and the trial site itself. In the short term, increased proportions of sugar beet in the crop rotation at sites with no prior sugar beet cultivation could be tolerated, whereas in the long term there was almost always a significant yield loss. The most common reasons cited for this were the promotion of pests and pathogens such as *Heterodera schachtii*, *Rhizoctonia solani*, *Phoma betae* and *Cercospora beticola*, reduced microbiological activity in the soil and a heavy strain on phosphorus and potassium reserves.

The highest sugar beet root yield losses are often observed when increasing cropping concentration from 33 % (Smukalski and Rogasik, 1977; Wicke and Urban, 1978) or 50 % (Köppen et al., 1987; Wicke and Matthies, 1990) to 100 %. However, contrasting results have also been published. In crop rotations with sugar beet cropping concentrations of 16.7 %, 33 % and 100 %, for example, twelve years after the start of the trial Draycott et al. (1978) found the lowest root yield in the variant with 16.7 %. This was presumably due to a lack of potassium and/or sodium in this variant, which was caused by the cultivation of the complementary crops. In this study, therefore, the cropping concentration of sugar beet had no effect on yield level.

As sugar beet cropping concentration increases, infestation with the beet cyst nematode *H. schachtii* is of crucial significance for the level of yield loss. Numerous studies have demonstrated that as sugar beet cropping concentration increases and the sugar beet cropping interval decreases, the *H. schachtii* population grows and the root yield of sugar beet declines (Fischer et al., 1981a; Fichtner et al., 1984b; Wicke and Matthies, 1990; Liste et al., 1992; Deumelandt et al., 2010). Thus, infestation with *H. Schachtii* already causes significant yield losses when the cropping concentration is low. For instance, on a highly fertile Haplic Chernozem which was infested with nematodes, Fischer and Liste (1979) and Liste et al. (1990) identified the most significant drop in root yield between crop rotations with 25 % and 50 % cropping concentration. By contrast, these differences were less pronounced between the crop rotations with sugar beet cropping concentrations of 50 % to 75 % and 100 %. At a field trial set up in parallel, where the site was not infested with nematodes but had similar conditions in terms of climate and soil typology, root yield decreased similarly as cropping concentration increased. However, the clearest yield loss was not seen until the cropping concentration rose from 75 % to 100 %, and the yield difference between the extreme variants was also smaller than at the site infested with nematodes.

The *H. schachtii* population and the associated potential yield loss are however also influenced by the complementary crops grown in the crop rotation. Growing alfalfa (*Medicago* ssp.), for example, reduces the *H. schachtii* population to a greater extent than other non-host crops like winter wheat and potatoes (*Solanum tuberosum* L., Liste et al., 1992), because the cultivation of alfalfa can increase the proportion of parasitized *H. schachtii* cysts and reduce the vitality of larvae (Duda and Liste, 1991). The cultivation of nematode-resistant catch crops, such as mustard (*Sinapis alba* L.) and oil radish (*Raphanus sativus var. oleiformis* L.), can also reduce nematode infestation by up to 70 % and increase root yield by 10 % to 15 % (Heinrichs, 2011).

In addition to the influence of crop rotation pathogens, other effects of the preceding crop on root yield have been discussed. Hao et al. (2001a) for example claim that a higher root yield in sugar beet following a grainy legume instead of summer wheat as a preceding crop was due to smaller amounts of crop residues. When sugar beets are sown in the spring, these fewer residues would mean that the soil would heat up more quickly, in turn promoting the field emergence and juvenile growth of sugar beet plants. In contrast to this, Fischer et al. (1981a) attribute better juvenile growth in sugar beet plants following alfalfa as a preceding crop when compared to sugar beets in monoculture to more residual organic matter, and coupled with this improved soil structure and nutrient mobilisation. In general, a lower level of soil organic matter (Wicke and Matthies, 1990; Pfefferkorn and Körschens, 1991) and a less favourable soil structure or soil compaction (Sommer et al., 1981; Anderson and Peterson, 1985; Pabin et al., 1991; Hanse et al., 2011) have a negative impact on sugar beet yield. As described in the previous chapters, these parameters can in turn be modified by the cultivation of sugar beet, making them part of the crop rotation effects which are of relevance to crop yield.

Although, the relation between the parameter root yield and the position of sugar beet in crop rotations has been widely discussed in the literature, of the aforementioned studies only those by Draycott et al. (1978), Köppen et al. (1987), Hao et al. (2001a) and Deumelandt et al. (2010) published information on sugar content. In Draycott et al. (1978) and Hao et al. (2001a) there was no significant influence on sugar content. Deumelandt et al. (2010) however demonstrated a trend towards higher sugar content and, after deducting the standard molasses loss, a significantly higher white sugar content in monoculture compared to crop rotations with cropping concentrations of 20 % and 25 %. Due to the significantly higher root yield, the crop rotations with sugar beet cropping concentrations of 20 % and 25 % achieved a white sugar yield that was 21 % and 15 % higher respectively than in monoculture. On the other hand, Köppen et al. (1987) and Rychcik and Zawiślak (2002) reported lower sugar contents in monoculture than in crop rotations, and in a 9-field crop rotation with 22 % sugar beet and integration of alfalfa, Hlisnikovsky et al. (2014) also found a higher root yield and sugar content than in a sugar beet-summer wheat crop rotation.

So far there are no known results from the literature which demonstrate the influence of the crop rotation on the yield stability of sugar beets. Hlisnikovsky et al. (2014) reported that the root yield and sugar content in a crop rotation with 50 % largely depended on weather conditions, but not the crop rotation with 22 % sugar beet. This is also suggestive of an impact on yield stability, although it was not evaluated.

4 Aims and scope of the thesis

To be able to evaluate the influence of specialised sugar beet crop rotations on soil fertility and on yield and yield stability, especially in the context of sustainable intensification, further investigations are necessary.

Traditional methods of cultivating sugar beet have tended to result in a depletion of soil organic matter. The cultivation of sugar beet is therefore assigned the highest demand for organic matter in humus balancing. As such, it can also be assumed that specialised sugar beet crop rotations will also result in a strong decrease of soil organic matter. However, the VDLUFA’s *Standpunkt Humusbilanzierung* (official position on humus balancing, VDLUFA, 2014) notes a considerable need for research with regard to humus reproduction. Further long-term field trials need to be evaluated to be able to predict soil organic matter dynamics under different cultivation conditions. It should also be questioned whether the humus balance coefficients for sugar beet have been overestimated. The **first article** (chapter II, Götze et al., 2016b) will therefore examine the following hypothesis:

Hypothesis 1: *Under changing cultivation conditions, the soil organic matter content is reduced by increasing the sugar beet cropping concentration. The change in soil organic matter can be mapped to a sufficiently accurate degree using humus balances.*

To this end, soil organic carbon contents and stocks as well as microbial biomass carbon content were identified in crop rotations with 50 %, 75 % and 100 % sugar beet at a long-term field trial in Etzdorf (Saxony-Anhalt). In addition, humus balances were calculated for these crop rotations using the program REPRO (Hülsbergen, 2003) and compared with the results of the soil tests.

Parts of the methods used to cultivate sugar beet may, under certain conditions, impair soil structure and its functionality (Boizard et al., 2002; Koch et al., 2008). In order to evaluate the effects of specialised sugar beet crop rotations on impairments to the soil structure and draw comparisons with other crop types, the soil compaction risk of the crop-specific cultivation methods should be calculated, taking into account soil water content. Here it is also necessary to consider typical crop rotations across several rotations (cycles). On the one hand this is to account for the effects of preceding crops, e.g. due to altered sowing times for the subsequent crop, and on the other to allow weather-related annual fluctuations in soil water content to be incorporated into the risk assessment. Such approaches have yet to be published in the scientific literature. In the **second article** (chapter III, Götze et al., 2016a), the following hypothesis will therefore be examined:

Hypothesis 2: *Integrating sugar beet in crop rotations increases the risk of soil compaction in the whole crop rotation due to the operation-specific technology used and high water contents at harvest.*

The basis for this is a crop rotation experiment in Aiterhofen (Bavaria) where soil physical parameters were determined to characterise the soil structure. In addition, the soil compaction risk of the crop rotations examined was calculated based on a model farm using the “Soil compaction risk” module in REPRO (Rücknagel et al., 2015), with the validity of the module having been examined in advance.

The impact of the sugar beet cropping interval on yield is sufficiently documented in the literature (Fischer and Liste, 1979; Deumelandt et al., 2010). In most cases, increasing proportions of sugar beet in the crop rotation are associated with a reduction in the sugar beet yield, especially root yield. The extent of this reduction in yield is highly dependent on infestation with *H. schachtii*, although it can be attenuated by integrating alfalfa in the crop rotation. However, so far there are no known results in the literature which demonstrate the influence of crop rotation on the yield stability of sugar beet. The **third article** (chapter IV, Götze et al., 2017) will examine the following hypothesis:

Hypothesis 3: *The yield stability of sugar beet decreases with an increasing concentration of sugar beet in the crop rotation and with a decreasing cropping interval for sugar beet..*

To this end, the root yield and technological quality of sugar beet as well as the white sugar yield for crop rotations with sugar beet cropping concentrations of between 20 % and 100 %, and a sugar beet cropping interval of none to four years, were evaluated over a period of 13 years, and yield stability was also determined. Again, the basis of these investigations was the long-term field trial in Etzdorf.

The hypotheses are discussed in a concluding **epilogue**. Taking into account the existing results and the current state of knowledge, it summarises potential negative effects of specialised sugar beet crop rotations on soil fertility and on the yield performance of sugar beets, and also presents possible strategies for avoiding such effects.

II Sugar beet rotation effects on soil organic matter and calculated humus balance in Central Germany

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Abstract

In order to quantify the influence of land use systems on the level of soil organic matter (SOM) to develop recommendations, long-term field studies are essential. Based on a crop rotation experiment which commenced in 1970, this paper investigated the impact of crop rotations involving increased proportions of sugar beet on SOM content. To this end, soil samples were taken in 2010 and 2012 from the following crop rotation sequences: sugar beet-sugar beet-winter wheat-winter wheat (SB-SB-WW-WW = 50%), sugar beet-sugar beet-sugar beet-winter wheat (SB-SB-SB-WW = 75%), sugar beet-grain maize (SB-GM = 50%) and sugar beet-monoculture (SB = 100%); these were analysed in terms of total organic carbon (TOC) and microbial biomass carbon (MBC) content, MBC/TOC ratio and the TOC stocks per hectare. In addition, humus balances were created (using the software REPRO, reference period 12 years) in order to calculate how well the soil was supplied with organic matter. In the field experiment, harvest by-products (WW and GM straw as well as SB leaves) were removed. After 41 years, no statistically significant differences were measured between the crop rotations for the parameters TOC, MBC, MBC/TOC ratio and the TOC stock per hectare. However, the calculated humus balance was significantly affected by the crop rotation. The calculated humus balance became increasingly negative in the order SB-SB-WW-WW, SB-SB-SB-WW, SB monoculture and SB-GM, and correlated with the soil parameters. The calculated humus balances for the reference period did not reflect the actual demand for organic matter by the crop rotations, but instead overestimated it.

1 Introduction

Supplying soils with enough organic matter to maintain stable levels of soil organic matter (SOM) is an important criterion of sustainable land use. SOM has a positive impact upon essential characteristics of soil fertility, although a supply of organic matter which exceeds the site's normal levels can cause increased mineralisation and nutrient loss (Johnston et al., 2009). Apart from site-related soil properties, SOM content is mainly influenced by cultivation practices (Christensen and Johnston, 1997). The amount of residual aboveground and below-ground biomass during a crop rotation influences the soil's total organic carbon (TOC) content as well as microbial biomass carbon (MBC) (Havlin et al., 1990; Karlen et al., 1994). Sugar beets (SB) are characterised by low levels of crop and root residues, especially when compared to cereals (Klimanek, 1997), and as such they are thought to contribute little organic matter to the soil.

Furthermore, the frequency and intensity of soil tillage influences the conversion rate and the content of the SOM (Balesdent et al., 2000). This means that low SOM content may be expected in the case of crop rotation sequences with high proportions of root crops which require intensive tillage, such as SB and potatoes. Steinbrenner and Smukalski (1984) reported that the crop rotation system with the highest proportion of SB and potatoes also had the lowest SOM content. Beck (1975) also arrived at similar conclusions in his investigations, in which potato and SB monoculture displayed significantly lower TOC contents than cereal monoculture. By contrast, Deumelandt et al. (2010) were only able to ascertain a tendency towards slightly lower TOC content in SB monoculture when compared with SB grown in crop rotation. The same applies for Kunzová (2013) who observed no differences in terms of TOC content in a 9-field crop rotation system when compared to two-phase crop rotation with SB and spring barley.

The impacts of agricultural land use on SOM can be estimated using humus-balancing models (Brock et al., 2013). A stable calculated humus balance is also necessary in the context of agricultural subsidies and farms need to prove that their soil has a sufficient supply of organic matter. In the corresponding benchmark values for balancing humus (Körschens et al., 2005), SB, potatoes and silage maize are considered the highest in terms of depletion of TOC. Therefore, crop rotations with high proportions of these crops require considerable amounts of organic matter in order to maintain a stable calculated humus balance. For farms carrying out intensive SB production, which also incorporate other root crops as part of their crop rotations, Deumelandt and Christen (2008) calculated negative balances, which were attributed to an insufficient supply of organic matter.

In future cropping systems, it is possible that crop rotations with increased frequency of SB will become established in practice. On the one hand, a high yield potential and large amounts of readily fermentable carbohydrates make SB particularly suitable for biogas production (Hoffmann et al., 2012; Starke and Hoffmann, 2014), offering an alternative to growing maize (Jacobs et al., 2014). On the other hand, if quota regulations for SB are discontinued, changes in global sugar prices may result in increased frequency of SB in crop rotations. If global prices rise, the growing demand will be met by increasing SB acreage in existing growing areas (Gocht et al., 2012). In order to minimise transportation costs, declining global prices would result in intensification in the areas sown with SB which are situated in close proximity to processing factories (Isermeyer et al., 2005). Therefore, these changing economic requirements could lead to increasing cropping concentrations for SB in crop rotation. Thus, considering the SB´s status as a humus depleting crop, this would likely affect the SOM content.

However, appropriate long-term field experiments are necessary to quantify the influence of SB in crop rotations on SOM (Märländer et al., 2003). The high degree of spatial and temporal variability of TOC dynamics mean that reproducible results cannot be expected until a trial period of at least 20 years has elapsed (Körschens, 2010). The study presented here is based on the SB crop rotation experiment in Etzdorf, Germany, which commenced in 1970. This experiment compares crop rotations with increased proportions of SB including monoculture, to investigate impacts on TOC and MBC content, as a parameters linked to SOM and the convertible fraction of SOM respectively. The TOC stock per hectare and the MBC/TOC ratio were also measured and calculated humus balances prepared to ascertain whether they correlate with the identified soil parameters. The overall aim was to determine whether effects of crop rotation on soil parameters can be predicted using calculated humus balances.

2 Materials and methods

2.1 Field site and experimental design

The investigations were performed at a long-term field trial in Etzdorf (Saxony-Anhalt, Germany, 51°43' N; 11°76' E, altitude 134 m), which was commenced in 1970 and is run by the University of Halle-Wittenberg. The soil type was classified as a Haplic Chernozem (FAO 2006). The soil texture in the tilled soil (0-30 cm) was that of a silt loam (250 g kg^{-1} clay, 50 g kg^{-1} sand), while the pH value was 6.9. For the calculated humus balance reference period (1998 to 2011), the mean annual temperature was 9.3°C (min. 7.6°C, max. 10.1°C), and the mean annual precipitation was 491 mm (min. 350 mm, max. 663 mm).

The crop rotation experiment had a block design with two replications (plot size 26.4 m², 8.8 m x 3.0 m), with each crop rotation field sown every year. Four crop rotations were compared for the investigations presented here; they were characterised by increasing concentrations of sugar beet (SB, *Beta vulgaris* L.) and decreasing SB cropping intervals (Table II-1). The other crops in the crop rotations were winter wheat (WW, *Triticum aestivum* L.) and grain maize (GM, *Zea mays* L.).

Table II-1. Crop rotations at the long-term field trial Etzdorf (SB - sugar beet; WW - winter wheat; GM - grain maize).

	Crop rotation			
Year 1	SB[a]	SB[a]	SB[a]	SB[a]
Year 2	SB	SB	GM	SB
Year 3	SB	SB	SB	WW
Year 4	SB	WW	GM	WW
SB concentration [%]	100	75	50	50
Cropping interval for SB [years]	0	1/0/0	1	2/0

[a] plots with soil analysis

As the experiment has progressed, management of the land has changed somewhat. Firstly, the SB-GM rotation began in 1986 and, secondly, the application of farmyard manure was modified during the last two decades. From 1970 to 1991, 10 t ha^{-1} of farmyard manure was added each year. From 1991 until 2006, the plots were fertilized every three years with 30 t ha^{-1} farmyard manure. Since 2007, no farmyard manure was applied.

Mineral nitrogen fertilizer was applied at 160 kg N ha^{-1} on SB and GM, while the amount used on the WW depended on the requirements calculated for each year. The resulting crop residues (SB leaves, WW straw) were removed from all plots. Primary soil tillage was performed in the autumn using a mouldboard plough to a depth of 30 cm. Before SB and WW were sown, a rotary harrow was used for seed-bed preparation, while for GM, seed-bed preparation, using a rotary tiller as well, was combined with the sowing itself.

2.2 Soil analysis

In the spring of 2010 (41st trial year) and 2012 (43rd trial year), soil samples were taken from the first crop rotation field (SB plots) of the crop rotations described in Table II-1. Thus, for the SB monoculture and the SB-GM rotation soil samples were taken from the same plots in both years, whereas for the SB-SB-SB-WW and SB-SB-WW-WW rotation, soil samples were taken from different plots in both years. For sampling, the plots were divided into a lower and an upper sub-plot. In each of these plot halves, a boring rod was used to extract a composite sample from soil depths of 0-30 cm and 30-45 cm in order to determine the soil's chemical and biological parameters (soil depth 30 cm only). Soil cores were also extracted (n = 4 per depth, V = 250 cm^3, h = 6 cm, diameter = 7.28 cm) in order to determine dry bulk density at soil depths 2-8 cm, 12-18 cm, 22-28 cm and 35-41 cm.

Dry combustion (ISO 10694:1995-03-01) was used to analyse the total carbon content (TC) of the boring rod samples. The total amount of organic carbon (TOC) was calculated by subtracting the carbonate content (volumetric method, ISO 10693:1995-03-15) from TC content. The substrate-induced respiration method according to Anderson and Domsch (1978) and Heinemeyer et al. (1989) was used to determine the level of microbial biomass carbon (MBC). In order to calculate dry bulk density, the soil cores were dried at 105°C for 48 h, until their mass remained constant (ISO 11272:1998).

2.3 Calculating TOC stock per hectare

For each of the crop rotations investigated, the TOC stock per hectare was calculated using a method by Ellert and Bettany (1995) (equations II-1 to II-5, Table II-2). This did not involve comparing equal soil depths, but rather equal soil masses. The plot half with the greatest mass in the 0-30 cm sampling horizon was taken as a reference plot half. The plot halves with lower soil masses have the corresponding depth required for their mass to equal that of the reference plot half added to them from the underlying soil horizon (30-45 cm). The TOC stock per hectare was thus derived from the amount of TOC at a soil depth of 0-30 cm plus the amount of TOC in the soil horizon required additionally. The dry bulk density at a soil depth of 0-30 cm was the average value from the soil core sampling depths of 2-8 cm, 12-18 cm and 22-28 cm. For the soil depth of 30-45 cm, the dry bulk densities of the soil cores from a soil depth of 35-41 cm were applied.

$$M_{TOC,equiv.} = M_{TOC,0-30cm} + M_{TOC,T_{add}} \quad \text{II-1}$$

$$M_{TOC,Tadd} = conc_{TOC,30-45cm} * \rho_{b,30-45cm} * T_{add} * \ 10\,000\ m^2\ ha^{-1} * 0.001\ t\ kg^{-1} \quad \text{II-2}$$

$$M_{TOC,0-30cm} = conc_{TOC,0-30cm} * \rho_{b,0-30cm} * T_{0-30cm} * \ 10\,000\ m^2\ ha^{-1} * 0.001\ t\ kg^{-1} \quad \text{II-3}$$

$$T_{add} = \frac{\left(M_{soil,equiv.} - M_{soil,0-30cm}\right) * 0.0001\ \mathrm{ha\ m^{-2}}}{\rho_{b\ 30-45cm}} \quad \text{II-4}$$

$$M_{soil,0-30cm} = \rho_{b,0-30cm} * T_{0-30cm} * \ 10\,000\ m^2\ ha^{-1} * 0.001\ t\ kg^{-1} \quad \text{II-5}$$

Table II-2. Description of symbols used in equations II-1 to II-5 (TOC - total organic carbon).

Symbol	Description	Unit
$M_{TOC,equiv.}$	TOC mass adjusted to equal soil masses	[t ha^{-1}]
$M_{TOC,0-30cm}$	TOC mass in 0-30 cm soil horizon	[t ha^{-1}]
$M_{TOC,T_{add}}$	TOC mass in additional soil horizon	[t ha^{-1}]
$M_{soil,equiv.}$	mass of heaviest soil at 0-30 cm	[t ha^{-1}]
$M_{soil,0-30cm}$	soil mass at 0-30 cm	[t ha^{-1}]
$conc_{TOC,0-30cm}$	TOC concentration at 0-30 cm	[g kg^{-1}]
$conc_{TOC,30-45cm}$	TOC concentration at 30-45 cm	[g kg^{-1}]
$\rho_{b,0-30cm}$	dry bulk density at 0-30 cm	[t m^{-3}]
$\rho_{b,30-45cm}$	dry bulk density at 30-45 cm	[t m^{-3}]
T_{0-30}	horizon depth	[m]
T_{add}	additional horizon depth needed to reach $M_{soil,equiv.}$	[m]

2.4 Calculated humus balance

The humus balances of the crop rotations investigated were calculated according to the Dynamic Humus Unit Method using the modelling software REPRO (REPROduction of soil fertility; (Hülsbergen, 2003; Küstermann et al., 2008; Küstermann et al., 2010). Here, a humus unit (HU) is equal to one tonne of humus with 50 kg N and 580 kg C. For the field trial considered in this paper, where the by-products – WW and GM straw as well as SB leaves – were removed from the field, organic fertilizer was only supplied until 2006 by regular addition of farmyard manure. For one tonne of fresh mass farmyard manure, 0.07 humus units, or 40.6 kg humus-C, were taken into account. The humus balance was calculated by taking the calculated humus supplied by the farmyard manure and subtracting the calculated humus demand of the individual crops (equation II-6, following Brock et al., 2013). Following Hülsbergen (2003), the calculated humus requirements of the humus-depleting crops SB, GM and WW were identified for each plot and each year using equations II-7, II-8 and II-9. The balancing coefficients were adjusted to the yield and fertilization levels as well as site conditions. Table II-3 shows the description of the symbols used in equations II-7, II-8 and II-9 and the associated standard values. Fresh plant mass were measured in the field trial. For WW and GM the dry matter content of the main-product was also measured and initial yields given based on a dry matter content of 86.0 %. The dry-matter contents of SB, SB leaf as well as WW straw and GM straw were based on standard values. By-product yields were calculated from the fresh matter yields by a main product/by product ratio of 1.25 for WW and GM and 1.43 for SB. Nitrogen contents were also based on standard values. For WW and GM, the N content was adjusted to the nitrogen fertilization rate and the yield.

Calculated humus balances were drawn up for the plots on which soil samples were extracted during the investigation in the years 2010 and 2012. Here, a reference period of 12 years was applied. For the investigation year 2010, the humus balances from the years 1998 to 2009 are calculated, and for the investigation year 2012 the humus balances from the years 2000 to 2011. The calculated humus balance is given in kg humus-C ha^{-1} a^{-1}, and is the mean of the balance values calculated for the corresponding reference periods.

$$humus\ balance = \ humus\ supply\ -\ humus\ demand\ (C_{hdc}) \qquad \text{II-6}$$

$$C_{hdc} = \frac{N_u - \left(N_{oMF} * \frac{U_{MF}}{100}\right) - \left(N_I * \frac{U_I}{100}\right)}{n_{FM} * \frac{U_{FM}}{100}} * H_{FM} \qquad \text{II-7}$$

$$N_u = Y_{mp} * \frac{d_{mp}}{100} * n_{mp} + \ Y_{bp} * \frac{d_{bp}}{100} * n_{bp} \qquad \text{II-8}$$

$$N_{oMF} = \ Y_{mp} * \frac{d_{mp}}{100} * n_{mp} \qquad \text{II-9}$$

Table II-3. Description of symbols used in equations II-7, II-8 and II-9 and associated standard values (HU - humus unit, DM - dry matter, DM_{org} - organic dry matter, SB - sugar beet, WW- winter wheat, GM - grain maize).

Symbol	Description	Value
C_{hdc}	coefficient for humus-depleting crops [HU $ha^{-1}a^{-1}$]	--
N_u	nitrogen uptake [kg ha^{-1} a^{-1}]	see Table II-7 and Table
N_{oMF}	mineral nitrogen fertilizer input (optimum) [kg ha^{-1} a^{-1}]	see Table II-7 and Table
N_I	nitrogen immissions [kg ha^{-1} a^{-1}]	20.00
U_{MF}	utilization coefficient for N_{MF} [%]	83.67
U_I	utilization coefficient for N_I [%]	83.67
U_{FM}	utilization coefficient for n_{FM} [%]	83.67
n_{FM}	nitrogen content, farmyard manure [kg t^{-1} DM_{org}]	30.00
n_{mp}	nitrogen content, main product [kg N dt^{-1} DM]	SB 0.78; WW[a] 2.22 (1.80-2.28); GM[a] 1.48 (1.35-1.50)
n_{bp}	nitrogen content, by–product [kg N dt^{-1} DM]	SB 2.30; WW[a] 0.58 (0.45-0.60); GM[a] 1.08 (1.00-1.10)
d_{mp}	dry matter content for main product [%]	SB 15.00; WW, GM 86.00
d_{bp}	dry matter content for by–product [%]	SB 23.00; WW, GM 86.00
Y_{mp}	fresh matter yield, main product [dt $ha^{-1}a^{-1}$]	data not shown
Y_{bp}	fresh matter yield, by–product [dt $ha^{-1}a^{-1}$]	data not shown
H_{FM}	coefficient of humification for farmyard manure	0.35

[a] Mean and range, depending on nitrogen fertilizer input and yield.

2.5 Statistical analysis

An analysis of variance was carried out using the program SAS (SAS Institute, 2008) in order to statistically evaluate the parameters TOC content, MBC content, MBC/TOC ratio and TOC stock per hectare. Prior to this, the data sets of the soil parameters were checked for normal distribution by conducting a Shapiro-Wilk test with the program Statistica (Statsoft, 2011). A mixed statistical model was used, in which the effects crop rotation, year, crop rotation*year, replication and replication*block were recognised as fixed. The plots sampled in the respective years of the investigation and the measured values of the plot halves were included in the model as random effects and repeated measures. Thus n = 4 values were allocated per crop rotation and year. The degrees of freedom were estimated according to Kenward and Roger (1997). An F-test was conducted to test the fixed effects for significance (α = 5 %). For the parameter dry bulk density, the program Statistica (Statsoft, 2011) was used to calculate the means and standard deviations for the crop rotations in the respective year of the investigation and for the depths sampled. Thus n = 16 values were allocated per crop rotation, year and depth. An analysis of variance was also carried out for the parameter humus balance by using the program SAS (SAS Institute, 2008). A mixed model was used with crop rotation and year as fixed effects and block as a random effect. Because of two field replications n = 2 values were allocated by crop rotation and year. The program Statistica (Statsoft, 2011) was used to test whether the calculated humus balances correlated (Pearson) with the soil parameters analysed – TOC content, MBC content, MBC/TOC ratio and TOC stock per hectare. To do this, for each crop rotation the mean humus balance values and the mean soil parameter values from both years were calculated and correlated against each other; n = 1 pair of values was thus allocated per crop rotation.

3 Results

3.1 Soil parameters

3.1.1 TOC content

TOC content at a soil depth of 0-30 cm was not significantly influenced by crop rotation, but was by year (Table II-4). The combined TOC contents were higher in 2010 than in 2012 (Figure II-1). The differences between the individual variants were small, with the difference between the crop rotation with the highest and lowest TOC content differing by 0.7 g kg^{-1} in 2010 and 1.0 g kg^{-1} in 2012. Table II-5 shows the TOC content at a soil depth of 30-45 cm, along with the corresponding standard deviations. Crop rotation and year had no significant impact on TOC content, and nor were there any significant crop rotation*year interactions (Table II-4).

Table II-4. Probability values from F-test of fixed effects at the long-term field trial Etzdorf after 40 years of trial duration (CR - crop rotation, R - field replication, TOC - total organic carbon, MBC - microbial biomass carbon).

Effect	TOC [g kg^{-1}] 0-30 cm	TOC [g kg^{-1}] 30-45 cm	TOC [t ha^{-1}]	MBC [g kg^{-1}] 0-30 cm	MBC/TOC [%] 0-30 cm	Humus balance [kg humus-C ha^{-1}a^{-1}]
CR	0.15	0.91	0.11	0.59	0.63	<0.01
Year	0.02	0.14	0.43	<0.01	0.06	0.15
CR*Year	0.94	0.17	0.91	0.43	0.60	0.67
R	0.31	<0.01	0.11	0.04	<0.01	--
R*Block	0.25	0.08	0.20	0.03	<0.01	--

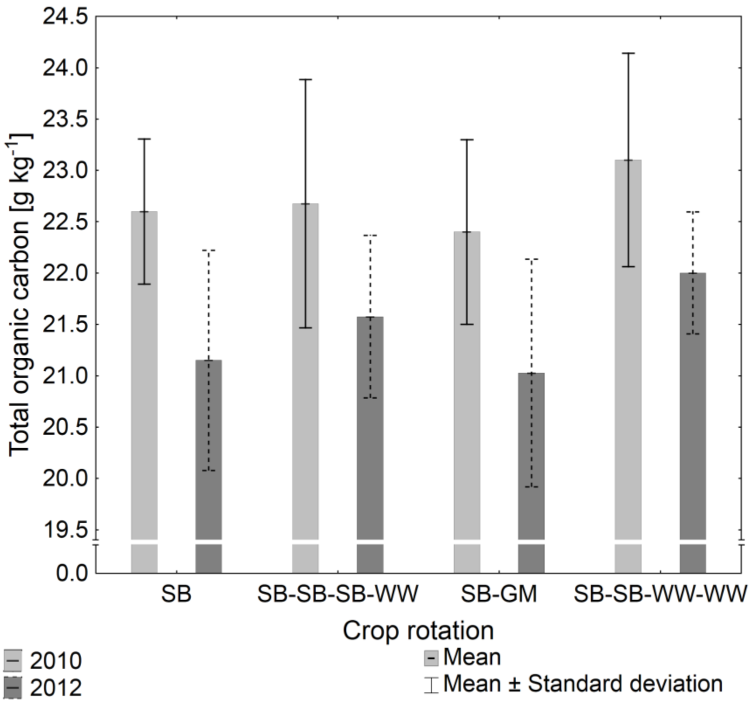

Figure II-1. Total organic carbon (TOC) content in the 0-30 cm soil layer at the long-term field trial Etzdorf after 40 years of trial duration (SB - sugar beet, WW - winter wheat, GM - grain maize).

Table II-5. Total organic carbon (TOC) content (± standard deviation) in the 30-45 cm soil layer for calculating TOC stock per hectare at the long-term field trial Etzdorf after 40 years of trial duration (SB - sugar beet, WW - winter wheat, GM - grain maize).

		Crop rotation			
Parameter	Year	SB	SB-SB-SB-WW	SB-GM	SB-SB-WW-WW
TOC	2010	18.3 (2.4)	17.5 (3.5)	16.6 (3.8)	15.7 (1.9)
[g kg^{-1}]	2012	18.4 (2.1)	19.2 (2.6)	19.9 (1.6)	18.8 (2.5)

3.1.2 MBC content and MBC/TOC ratio

Crop rotation had no significant effect on MBC content at a soil depth of 0-30 cm (Table II-4). In the year 2010, combined MBC contents were higher than in 2012 (Figure II-2). The MBC/TOC ratio (Figure II-3) indicated the share of MBC content as a percentage of TOC content. It was not significantly influenced by crop rotation and by year (Table II-4). The combined MBC/TOC ratio was higher in 2010 than in 2012.

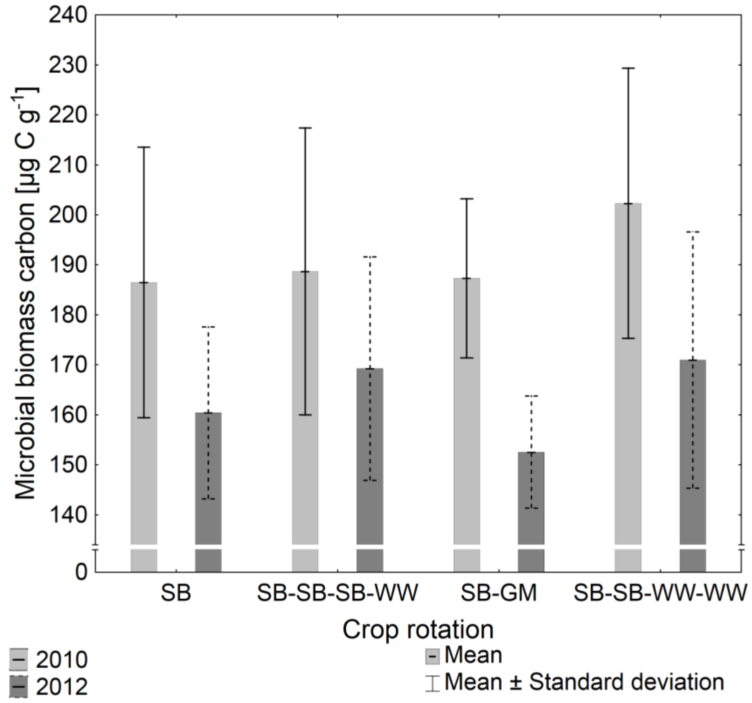

Figure II-2. Microbial biomass carbon (MBC) content in the 0-30 cm soil layer at the long-term field trial Etzdorf after 40 years of trial duration (SB - sugar beet, WW - winter wheat, GM - grain maize).

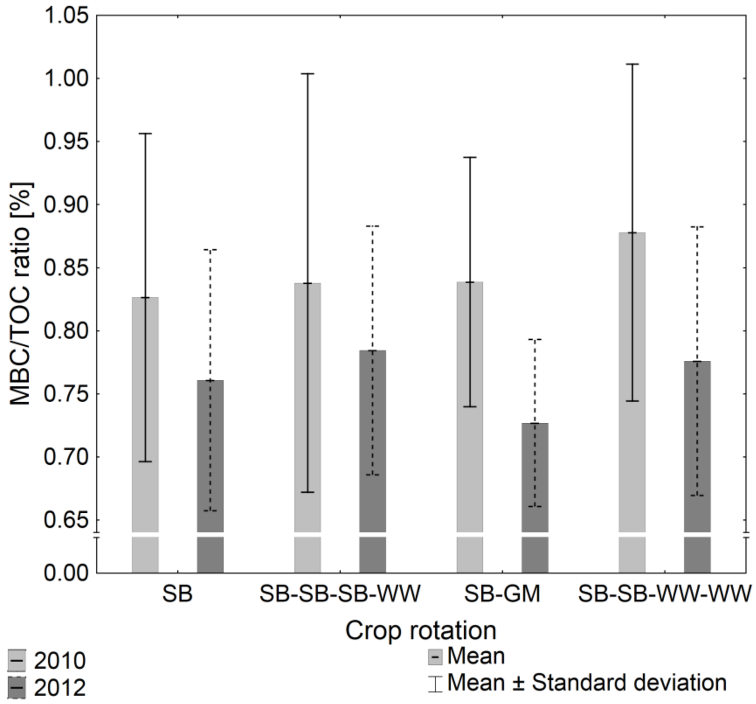

Figure II-3. MBC/TOC ratio in the 0-30 cm soil layer at the long-term field trial Etzdorf after 40 years of trial duration (MBC - microbial biomass carbon, TOC - total organic carbon, SB - sugar beet, WW - winter wheat, GM - grain maize).

3.1.3 TOC stock per hectare

The dry bulk densities required to calculate the TOC stock per hectare are given in Table II-6. At soil depths 2-8 cm and 12-18 cm, all crop rotations were characterised by higher dry bulk densities in 2010 than in 2012. A mass of 4353 t ha^{-1} was calculated as a reference soil mass for the soil horizon of 0-30 cm. Year and crop rotation had no significant impact on TOC stock per hectare (Table II-4). The difference between the crop rotations with the lowest and the highest stocks of TOC per hectare was 2.9 t ha^{-1} in 2010 and 3.0 t ha^{-1} in 2012 (Figure II-4).

Table II-6. Dry bulk density [t m^{-3}] (± standard deviation) for tested crop rotations in 2010 and 2012 at the long-term field trial Etzdorf (SB - sugar beet, WW - winter wheat, GM - grain maize).

Soil depth [cm]	Crop rotation SB		SB-SB-SB-WW		SB-GM		SB-SB-WW-WW	
				2010				
2-8	1.28	(0.06)	1.30	(0.06)	1.24	(0.05)	1.25	(0.07)
12-18	1.46	(0.06)	1.49	(0.07)	1.43	(0.07)	1.44	(0.06)
22-28	1.45	(0.05)	1.43	(0.06)	1.46	(0.04)	1.42	(0.04)
35-41	1.38	(0.06)	1.34	(0.10)	1.36	(0.04)	1.36	(0.05)
				2012				
2-8	1.14	(0.06)	1.10	(0.05)	1.15	(0.10)	1.12	(0.04)
12-18	1.26	(0.06)	1.29	(0.08)	1.27	(0.11)	1.29	(0.15)
22-28	1.43	(0.08)	1.41	(0.09)	1.42	(0.08)	1.38	(0.10)
35-41	1.42	(0.07)	1.40	(0.09)	1.41	(0.06)	1.34	(0.06)

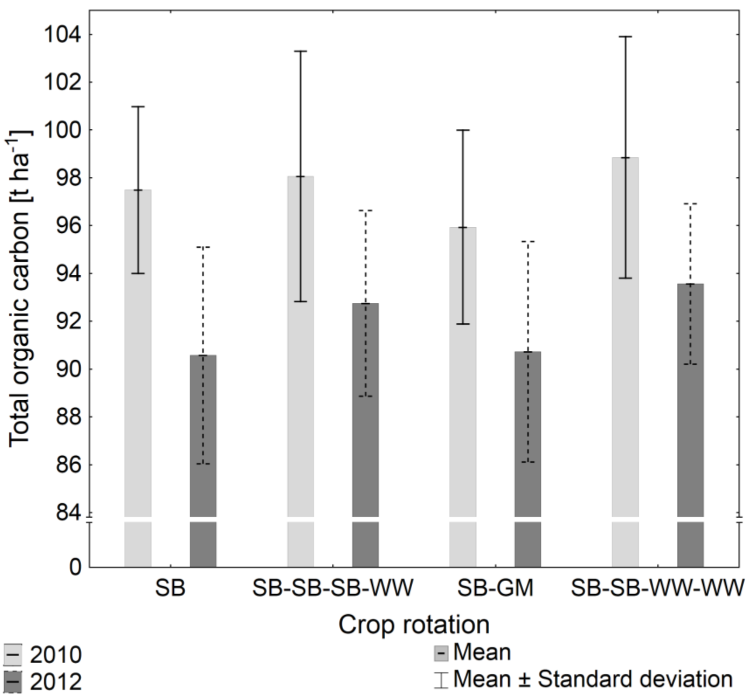

Figure II-4. Total organic carbon (TOC) stocks per hectare based on 4353 t ha^{-1} reference soil mass at soil depth 0-30 cm at the long-term field trial Etzdorf after 40 years of trial duration (SB - sugar beet, WW - winter wheat, GM - grain maize).

3.2 Calculated humus balance and correlations

The SB-GM rotation displayed the highest calculated nitrogen uptake in both reference periods and the lowest nitrogen uptake was observed for SB monoculture (Table II-7). In both reference periods, the calculated mineral nitrogen fertilizer input (optimum) was lowest for the SB monoculture and highest for the SB-SB-WW-WW rotation. Crop rotation had a significant effect on the calculated humus balance (Table II-4). In both periods, negative humus balances were calculated for all of the crop rotations investigated (Figure II-5). The calculated humus balance decreased in the order: SB-SB-WW-WW > SB-SB-SB-WW > SB monoculture > SB-GM. The difference between the SB-GM rotation and SB-SB-WW-WW rotations was -178 kg humus-C ha^{-1} a^{-1} for the period 1998-2009 and -234 kg humus-C ha^{-1} a^{-1} for the period 2000-2011. For all parameters, positive correlations with the calculated humus balance are significant at a p-value ≤ 0.05 (Figure II-6).

Table II-7. Calculated nitrogen uptake (Nu) [kg ha^{-1} a^{-1}] and mineral nitrogen fertilizer input (optimum) (NoMF) [kg ha^{-1} a^{-1}] for the reference periods 1998-2009 and 2000-2011 at the long-term field trial Etzdorf (SB - sugar beet, WW- winter wheat).

Year	SB			SB-SB-SB-WW			SB-SB-SB-WW		
	Crop	N_u	N_{oMF}	Crop	N_u	N_{oMF}	Crop	N_u	N_{oMF}
1998	SB	235	100	SB	227	97	--	--	--
1999	SB	238	102	SB	245	105	--	--	--
2000	SB	188	80	SB	168	72	SB	238	102
2001	SB	181	77	WW	198	164	SB	172	73
2002	SB	155	66	SB	186	79	SB	157	67
2003	SB	240	102	SB	225	96	WW	127	105
2004	SB	200	85	SB	187	80	SB	222	95
2005	SB	180	77	WW	224	185	SB	185	79
2006	SB	189	81	SB	204	87	SB	190	81
2007	SB	137	58	SB	160	68	WW	172	142
2008	SB	212	90	SB	144	61	SB	227	97
2009	SB	213	91	WW	211	176	SB	236	101
2010	SB	121	52	--	--	--	SB	164	70
2011	SB	230	98	--	--	--	WW	203	168
mean 1998-2009		197	84		198	106		--	--
mean 2000-2011		187	80		--	--		191	98

Table II-7. Continuation.

Year	SB-GM			SB-SB-WW-WW			SB-SB-WW-WW		
	Crop	N_u	N_{oMF}	Crop	N_u	N_{oMF}	Crop	N_u	N_{oMF}
1998	SB	269	115	SB	244	104	--	--	--
1999	GM	145	92	SB	221	94	--	--	--
2000	SB	238	102	WW	188	156	SB	227	97
2001	GM	177	111	WW	187	155	SB	171	73
2002	SB	210	90	SB	201	86	WW	155	128
2003	GM	220	139	SB	246	105	WW	134	111
2004	SB	228	97	WW	153	126	SB	237	101
2005	GM	260	164	WW	200	165	SB	178	76
2006	SB	225	96	SB	215	92	WW	183	151
2007	GM	213	134	SB	169	72	WW	185	153
2008	SB	239	102	WW	243	200	SB	196	84
2009	GM	304	191	WW	189	157	SB	200	85
2010	SB	186	79	--	--	--	WW	215	177
2011	GM	97	65	--	--	--	WW	185	153
mean 1998-2009		227	119		205	126		--	--
mean 2000-2011		216	114		--	--		189	116

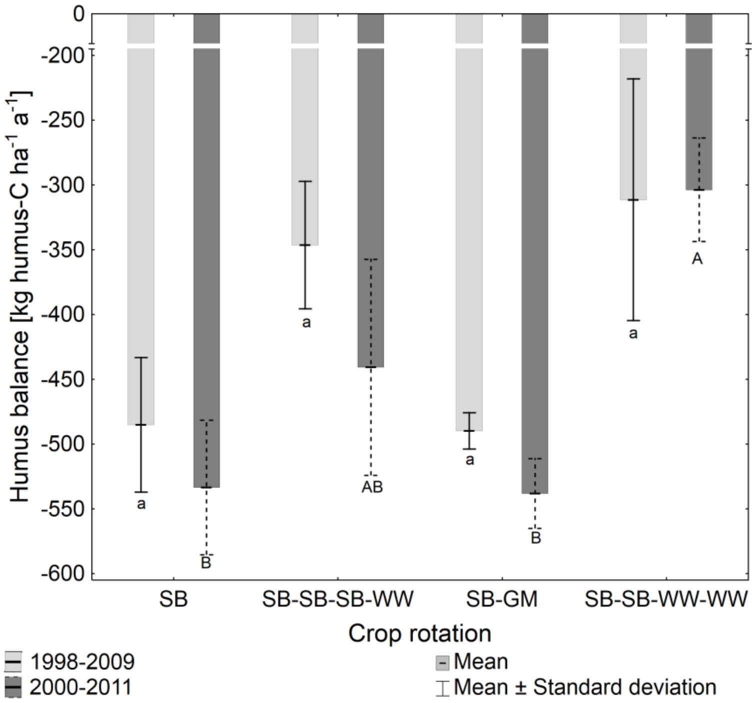

Figure II-5. Calculated humus balance of tested crop rotations at the long-term field trial Etzdorf. Different lower case letters indicate significant differences for the reference period 1998-2009, different upper-case letters indicate significant differences for the period 2002-2011 ($\alpha = 0.05$, $n = 2$) (SB - sugar beet, WW - winter wheat, GM - grain maize).

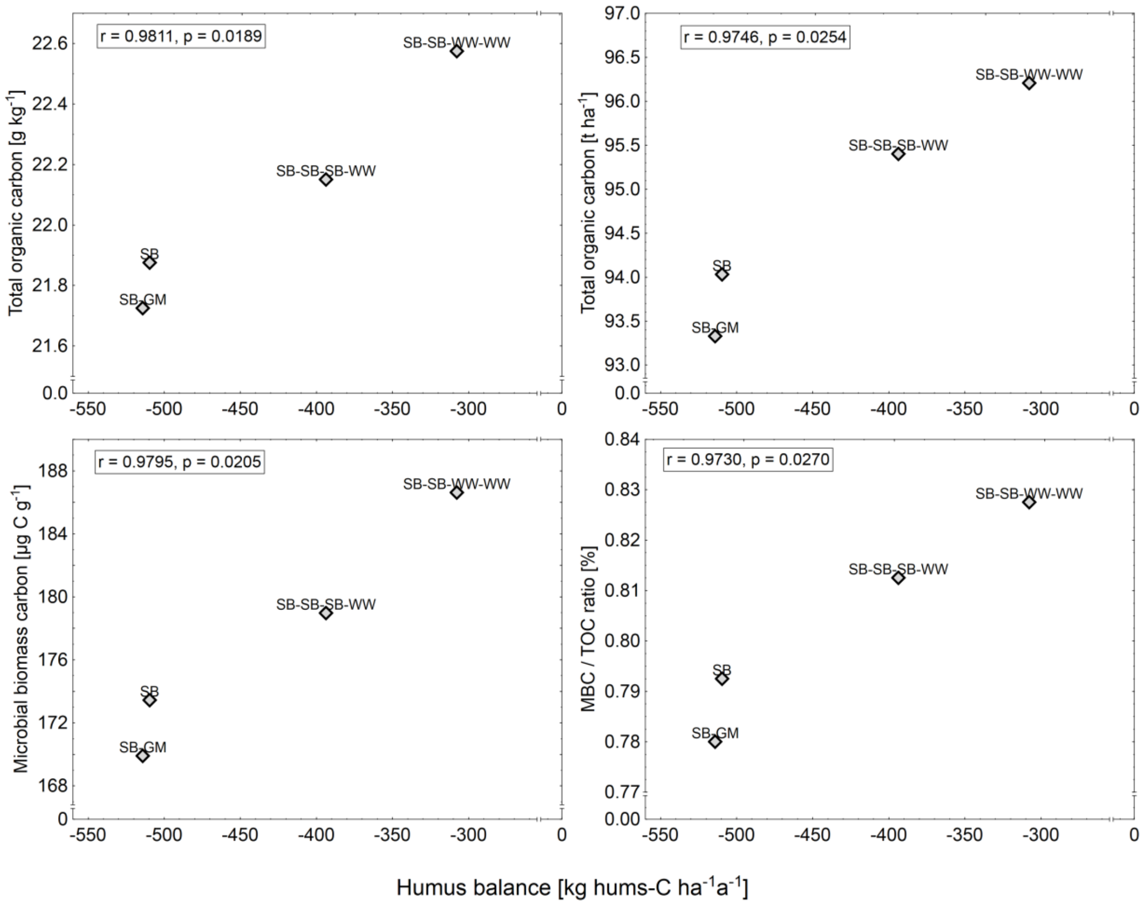

Figure II-6. Correlations (Pearson) between the calculated humus balance and the identified soil parameters at the long-term field trial Etzdorf (TOC - total organic carbon, MBC - microbial biomass carbon).

4 Discussion

4.1 Soil parameters

The quantity and quality of SOM is often used to evaluate the sustainability of agricultural land use (Carter, 2002). However, the high degree of spatial and temporal variability of carbon dynamics means that changes in SOM content cannot be mapped until a trial period of decades has elapsed (Körschens, 2010). Therefore, the data delivered by long-term field experiments about the changes in SOM as a result of different agricultural management practices, are important to assess management-related modifications to SOM content before implementing a planned change of land use. Changes in SOM content are determined based on the measurement of changes in TOC content, because TOC is the major component of SOM and thus SOM content is usually calculated by multiplying TOC content by a factor of 1.724 (Körschens et al., 1998). Management-related changes in TOC content also impact upon MBC content (Collins et al., 1992). These two parameters can therefore be used to describe the influence of management practices on SOM content, with MBC content revealing changes more quickly (Joergensen et al., 1994).

Körschens et al. (1998) divided the SOM into at least two fractions: (i) relatively inert fraction, which is hardly involved in decomposition processes and remains in soils over many decades. This part does not depend on fertilization or cropping but closely correlates with the clay content. (ii) The second part is mineralizable and decomposable and can be divided into further fractions. This convertible part of the SOM – which also includes the MBC content – is influenced by management. As such, parameters of the convertible SOM fraction also need to be used in order to detect the impacts of certain management practices. In agricultural soils, MBC levels range between 200 and 1000 µg C g^{-1} (Martens, 1995). The MBC levels for the study presented here can therefore be described as low, but typical of chernozems (Altermann et al., 2005; Blagodatskii et al., 2008) and the same applies to the wide MBC/TOC ratio. Once organic matter has been added, the MBC/TOC ratio narrows, indicating the intake of easily convertible carbon (Anderson and Domsch, 1989). In this experiment, the crop rotations including WW and GM, where stubble was worked into the ground in autumn, did not display a significantly higher MBC/TOC ratio compared to the SB monoculture. The information from Anderson and Domsch (1989) suggesting that wider MBC/TOC ratios appear in monocultures rather than in crop rotations is not confirmed by these results.

Changes to TOC content which are attributable to other factors such as fertilization, tillage and crop rotation, generally only amount to approximately 0.1 g kg^{-1} or 0.5 t ha^{-1}, annually (Körschens et al., 1998). The temporal variability of TOC content is often higher such as the annual fluctuation of 1.5 g kg^{-1} reported by Körschens (2006) on a chernozem. Accordingly, the differences observed between the years 2010 and 2012 with regard to TOC content (g kg^{-1}) and the TOC stock per hectare (t ha^{-1}) cannot be attributed to an actual reduction in TOC of this amount, but are instead due to the temporal variability of SOM.

The results of all of the soil parameters investigated only show small, and non-statistically significant differences between the crop rotations. In the literature, clear differences have been reported for the TOC content (Campbell et al., 1991; Angers, 1992; Machado and Gerzabek, 1993; Karlen et al., 2006) and MBC content (Carter, 1986; McGill et al., 1986; Campbell et al., 1991; Karlen et al., 2006) between different crop rotations such as fallow land and perennial crops or rotations with legumes. Recent studies also indicate higher TOC contents for cropping systems with continuous cultivation compared to cropping systems including bare fallow (Halvorson et al., 2002; McConkey et al., 2003; Machado et al., 2006), which is attributed to high biomass production and corresponding higher crop residues. Anderson and Domsch (1989) as well as Dick (1992) report lower MBC levels in monocultures compared with crop rotations. For crop rotations and monoculture with SB, older literature often describes decreasing TOC content (Beck, 1975; Krauss et al., 1997) and SOM content (Steinbrenner and Smukalski, 1984), while in more recent studies the differences in TOC content are small when SB is grown (Deumelandt et al., 2010; Kunzová, 2013). The management practices used in the experiment provide the likely explanation for the small differences in TOC and MBC found between rotations. Relatively small differences in the soil's supply of organic matter to soil between the crop rotations investigated here are likely due to the removal of all residues, and the addition of farmyard manure for the first 36 years. Together with regular tillage, this overall management regime is the likely reasons for the lack of significant differences in MBC and TOC content. The application of organic fertilizers usually increases TOC content (McConkey et al., 2003; Machado et al., 2006; Koga and Tsuji, 2009) and MBC content (McGill et al., 1986). For experiments considering the factors crop rotation and tillage, tillage intensity clearly affects TOC content while crop rotation usually has a lower impact (Campbell et al., 1996; Hao et al., 2001b).

The decomposition rate of organic matter may also differ between different crop rotations. Monocultures are often marked by lower MBC levels (Anderson and Domsch, 1989; Dick, 1992), and the mineralization rate of N and C in soils increases with increasing MBC level (Kaiser, 1994). When adding organic matter to the soil, as done using farmyard manure application until 2006 in the presented study, the decomposition of the added organic matter would thus be expected to be more intensive in crop rotations compared to SB - monoculture and lead to the low differences in TOC stock per hectare. However there were no significant differences in MBC levels in the SB - monoculture compared to the crop rotations in either sampling year. However, the last application of farmyard manure was in 2006, and may not persist to influence the measured MBC levels in 2010 (4 years later) or 2012 (6 years later).

On the other hand, the high nitrogen fertilization together with farmyard manure could mask the differences in TOC content and TOC stock per hectare. Microbial activity, and thus decomposition rate, can also increase after application of mineral nitrogen fertilizer. This is due to a higher production of biomass, which can be used by microorganisms (Dick, 1992). Differences in the decomposition rate of organic matter by the crop rotations, as reported before, could be masked by the high nitrogen input level in the presented study.

Further, the removal of harvest by-products – WW and GM straw and SB leaves – in the study presented served to reduce the existing differences in the amounts and quality of crop and root residues of the respective crop types. Adding organic matter by leaving the by-products on the field has a positive impact on TOC content (Collins et al., 1992; Karlen et al., 1994; Lehtinen et al., 2014) and MBC content (Karlen et al., 1994; Blanco-Canqui and Lal, 2009). Nevertheless, removing these by-products may not always cause a reduction of the TOC and MBC content under all site conditions. For example after 49 trial years on a chernozem soil, Lemke et al. (2010) were unable to ascertain any differences in the TOC content of a wheat crop rotation where straw was harvested and one where the straw was not harvested. The authors concluded that provided otherwise sufficient site-adjusted fertilization occurs, certain quantities of organic matter can be removed without causing any measurable change in TOC content. Thus, one further explanation for the small differences in TOC in the present study may be that chernozems do not react sensitively enough to such management changes.

Even if the straw is removed as was done in this study, cereals leave behind more organic matter as root residues than SB (Klimanek, 1997), and can thus provide more carbon to the soil (Wiesmeier et al., 2014). However incorporating WW into the crop rotation did not significantly increase the TOC and MBC content as well as TOC stocks per hectare. Since the GM straw was also harvested in this trial, large quantities of organic matter were removed, rather like in silage maize cultivation which is known to reduce SOM content (Angers, 1992; Schmidt et al., 2000) but this also not confirmed by the results presented in this study. So, all crops investigated showed approximately equal effects on SOM content under the conditions and management at the Etzdorf site.

Furthermore, the results have to be discussed regarding contemporary cropping systems. Märländer et al. (2003) claimed that, under current management conditions, SB should no longer be regarded as a crop which severely depletes SOM. Firstly SB leaves currently remain almost entirely on the field, and secondly mechanical weed control is performed on just 10 % of beet acreage and is declining further. In addition, the percentage of conventionally tilled beet acreage has decreased to 50 % while mulching systems increase (Buhre et al., 2014). Thus, the management conditions at the SB rotation experiment Etzdorf do not represent the majority of current SB cropping systems in practice. As a long-term field trial, the SB rotation experiment Etzdorf is running with only slight changes since 1970 and that is the basis for its valuable results. However, it represents the common SB production methods of the 1970s, where SB leaf was usually harvested as fodder and the soil was usually ploughed because of weed and pest control. In future cropping systems such management practices also could be established in practice since SB leaves could be used for bioenergy production (Starke and Hoffmann, 2011) and pesticides could become constrained available because of environmental impacts and social criticism (Miles and Frewer, 2001).

4.2 Calculated humus balances and correlations with soil parameters

Calculated humus balances are tools which serve to map the effect of management on SOM content, an effect which can take decades in long-term trials to detect. Taking humus supply and humus demands as a basis for calculating how well a soil is supplied with organic matter, also facilitates the comparison of effects of different management systems at the local and regional level (Brock et al., 2012; Kasper et al., 2015). Optimum values for the calculated humus balance range from -75 kg humus-C ha^{-1} a^{-1} to 100 kg humus-C ha^{-1} a^{-1} (Körschens et al., 2005). Lower values indicate a degradation of SOM, whereas higher values indicate an increasing risk of uncontrolled N-mineralisation and N-losses. Unlike other methods of humus balancing, which employ fixed coefficients for humus-depleting crop types (e.g. (Körschens et al., 2005), the method applied here (Hülsbergen, 2003) modifies the coefficients depending on the nitrogen balance. In addition, the nitrogen utilization rates were adjusted depending on the site and weather conditions. Accordingly, this method directly relates to the processes of humus mineralisation. As such, it is not possible to model the changes in TOC or MBC content in the soil, because this requires further, horizon-specific soil parameters (Brock et al., 2013). Consequently we are only able to compare the calculated humus balances with the measured values; a temporally dynamic view is not possible. The correlation of the mean values over the two study years and reference periods of the respective crop types was used to compensate for the geographical and temporal fluctuations in TOC and MBC content.

The more negative the calculated humus balance, the higher the humus demand. As such, the humus demand of the crop rotations investigated increased in the following order: SB-SB-WW-WW > SB-SB-SB-WW > SB monoculture > SB-GM. This was in line with the results of Deumelandt and Christen (2008), who also showed that the highest humus demand was in crop rotations with high proportions of SB and other root crops. The results are also in accordance with other balancing methods, which assign the highest humus demand to SB (Körschens et al., 2005).

In this study, soil parameters correlated significantly and positively with the calculated humus balance values. Therefore the calculated humus balance is a practical tool for mapping differences in the crop rotations' individual demands for organic matter. Using the differences in the calculated humus balance between the SB-GM rotation and the SB-SB-WW-WW rotation, a difference in TOC stock per hectare of 2.5 t ha^{-1} is calculated for these crop rotations for the reference period of 12 years (mean of both reference periods). However the difference measured was 2.9 t ha^{-1} (mean of 2010 and 2012) and was not significant. Considering the trial duration of more than 40 years, larger differences would be expected based on the calculated humus balance values. Thus, the calculated humus balance for the 12 year reference period overestimated the actual humus demand under the given conditions at the site. A better adjustment could be achieved when using by-product yields, dry matter contents and nitrogen content which are ascertained in the field trial. Also adjusting the nitrogen utilization rates in the humus-balancing method may lead to a better estimate of the actual demand.

5 Conclusions

Contrary to expectations, after an experiment spanning more than 40 years no significant differences in TOC and MBC content, the MBC/TOC ratio or TOC stocks per hectare were observed between crop rotations with increasing proportions of SB. The removal of all crop residues, regular tillage and the addition of farmyard manure were associated management practices that may have limited the likelihood that crop rotation effects would be revealed. The difference in the demands made on SOM by the crop rotations investigated, which were based on calculated humus balances, correlated well with the soil parameters, although the actual requirement for organic matter is overestimated using the humus balance approach for a twelve-year period. Thus, the calculated humus balances do not predict the actual demand on organic matter by the crop rotations investigated at the long-term field trial Etzdorf. However, the calculated humus balance can be used to predict which crop rotation is likely to decrease SOM content on a larger scale.

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III Environmental impacts of different crop rotations in terms of soil compaction

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Abstract

Avoiding soil compaction caused by agricultural management is a key aim of sustainable land management, and the soil compaction risk should be considered when assessing the environmental impacts of land use systems. Therefore this project compares different crop rotations in terms of soil structure and the soil compaction risk. It is based on a field trial in Germany, in which the crop rotations (i) silage maize (SM) monoculture, (ii) catch crop mustard (Mu)_sugar beet (SB)-winter wheat (WW)-WW, (iii) Mu_SM-WW-WW and (iv) SB-WW-Mu_SM are established since 2010. Based on the cultivation dates, the operation specific soil compaction risks and the soil compaction risk of the entire crop rotations are modelled at two soil depths (20 and 35 cm). To this end, based on assumptions of the equipment currently used in practice by a model farm, two scenarios are modelled (100 and 50 % hopper load for SB and WW harvest). In addition, after one complete rotation, in 2013 and in 2014, the physical soil parameters saturated hydraulic conductivity (kS) and air capacity (AC) were determined at soil depths 2-8, 12-18, 22-28 and 32-38 cm in order to quantify the soil structure. At both soil depths, the modelled soil compaction risks for the crop rotations including SB (Mu_SB-WW-WW, SB-WW-Mu_SM) are higher (20 cm: medium to very high risks; 35 cm: no to medium risks) than for those without SB (SM monoculture, Mu_SM-WW-WW; 20 cm: medium risks; 35 cm: no to low risks). This increased soil compaction risk is largely influenced by the SB harvest in years where soil water content is high. Halving the hopper load and adjusting the tyre inflation pressure reduces the soil compaction risk for the crop rotation as a whole. Under these conditions, there are no to low soil compaction risks for all variants in the subsoil (soil depth 35 cm). Soil structure is mainly influenced in the topsoil (2-8 cm) related to the cultivation of Mu as a catch crop and WW as a preceding crop. Concerning kS, Mu_SB-WW-WW (240 cm d^{-1}) and Mu_SM-WW-WW

(196 cm d^{-1}) displayed significantly higher values than the SM monoculture (67 cm d^{-1}), indicating better structural stability and infiltration capacity. At other soil depths, and for the parameter AC, there are no systematic differences in soil structure between the variants. Under the circumstances described, all crop rotations investigated are not associated with environmental impacts caused by soil compaction.

1 Introduction

Indicator based assessments of the environmental impact of land use systems often do not include their influence on soil structure and the soil compaction risk (Castoldi and Bechini, 2010; Gaudino et al., 2014; Paracchini et al., 2015). However, soil structure is an important criterion of soil fertility (Mueller et al., 2010) since it determines the water and air balance as well as the rootability (Hartge, 1994) and the habitat quality for soil organisms (Birkás et al., 2004). Accordingly, soil compaction has a negative impact on the essential soil functions, resulting in increased environmental impacts (Nawaz et al., 2013). Preserving a functional soil structure and avoiding soil compaction are therefore important aspects of sustainable agriculture. Preventive measures, from using adapted chassis and tyres which protect the soil right up to Controlled Traffic Farming (CTF), are preferable since they are less expensive than taking subsequent remedial action (Chamen et al., 2015). Another method of preventive soil protection is to consider the effect of crop species on the formation of soil structure – as well as the soil compaction risk associated with cultivating these species – when planning the crop rotation.

Cultivating a crop can influence the soil structure by a number of factors. Aspects of root morphology and physiology are often discussed in this context, as well as the impact of harvest residues (Bronick and Lal, 2005; Blanco-Canqui and Lal, 2009). However, the effect of the crop or of the crop rotation on soil structure is often masked by the tillage method (Malhi et al., 2008) or by different levels of mechanical stress when driving over the soil with agricultural machinery (Boizard et al., 2002; Capowiez et al., 2009). A positive influence on soil structure is attributed to legumes and perennial forage crops. Specifically, cultivating them can result in increased macroporosity and hydraulic conductivity (McCallum et al., 2004) as well as aggregate stability (Reid and Goss, 1981), while dry bulk density and penetration resistance can decrease (Chan and Heenan, 1996).

Cultivating crops for bioenergy use aims to reduce environmental impacts, especially greenhouse gas emissions. Therefore crop rotations including crops with the lowest energetic input-output ratio are advantageous. In terms of biogas production under the conditions in Central Europe, silage maize (SM, *Zea mays* L.) and sugar beet (SB, *Beta vulgaris* L.) are suitable due to their high methane yields (Amon et al., 2007; Weiland, 2010; Brauer-Siebrecht et al., 2016). However, aspects concerning the impact on soil structure should be considered for the cultivation of crops for bioenergy use and only few results have been published on the impact of SB and SM on soil structure (Boizard et al., 2002; Deumelandt et al., 2010; Głąb et al., 2013; Jacobs et al., 2014). Therefore, this paper aims to identify the impacts of cultivating SB and SM in crop rotations with winter wheat (WW, *Triticum aestivum* L.) as well as of SM monoculture on soil structure. Due to the numerous factors which influence soil structure and the way they interact, it is expedient to integrate several methodological approaches to compare the soil structure related to different cultivation practices. To this end, physical soil parameters are recorded in a crop rotation experiment, in order to, first of all, present the crop-specific impact on soil structure under field trial conditions. Furthermore, model calculations are used to derive the soil compaction risk associated with common cultivation methods used for the entire crop rotation. This is based on a model farm which is assumed to use modern, standard equipment and refers to the operations and respective dates performed during the field trial. The validity of the model used is tested by field investigations into physical soil parameters. Finally, the results of both methods are used to assess the environmental impacts by soil compaction for different crop rotations.

2 Materials and methods

2.1 Field site and experimental design

A crop rotation field trial set up in 2010 in Aiterhofen (Germany, Lower Bavaria, 48°85' N; 12°63' E) forms the basis of these investigations. In this field trial, soil samples were taken in order to identify physical soil parameters and the soil structure. The field trial’s cultivation dates (driving dates) as well as site information serve to model the soil compaction risk.

The soil type is classified as a Luvisol (FAO, 2014), and the soil texture at a depth of 0-45 cm is that of a silt loam (205 g kg^{-1} clay, 128 g kg^{-1} sand). Long-term (1981-2010) average annual precipitation is 757 mm, and the mean annual temperature 8.6°C

(Straubing station, DWD, 2014). The field trial tests four crop rotations, containing SB, SM and WW as well as mustard as a catch crop (Mu, *Sinapis alba* L.) (Table III-1). The field trial has a block design with four replications, with each crop rotation field being sown every year on a separate plot. Every replication comprises 10 plots, each of them 420 m² in size.

Table III-1. Schemata for the crop rotations per replication at field site Aiterhofen (SB - sugar beet; WW - winter wheat; SM - silage maize; Mu - mustard catch crop, Mi - millet).

Crop rotation No.	Plot	Year 2010	2011	2012	2013	2014
1	1.1	SM	SM/Mi$^{\#}$	SM	SM*	SM*
2	2.1	Mu_SB	WW-1	WW-2	Mu_SB*	WW-1
	2.2	WW-1	WW-2	Mu_SB	WW-1	WW-2
	2.3	WW-2	Mu_SB	WW-1	WW-2	Mu_SB*
3	3.1	Mu_SM	WW-1	WW-2	Mu_SM*	WW-1
	3.2	WW-1	WW-2	Mu_SM	WW-1	WW-2
	3.3	WW-2	Mu_SM	WW-1	WW-2	Mu_SM*
4	4.1	SB	WW-1	Mu_SM	SB*	WW-1
	4.2	WW-1	Mu_SM	SB	WW-1	Mu_SM
	4.3	Mu_SM	SB	WW-1	Mu_SM	SB*

[*] plots with investigations into soil structure

[#] Mi was cultivated because of regional quarantine regulations

Primary tillage is performed as conservation tillage in the autumn, using a cultivator at a soil depth of 18 cm (working width 3 m). For SM, seedbed preparation is performed using a rotary harrow (working width 3 m, working depth 10 cm) and for SB using a seedbed cultivator (working width 5.6 m, working depth ≤ 5 cm). For WW, seedbed preparation is performed using a rotary harrow (working width 3 m, working depth ≤ 10 cm) in combination with the seeder. For the spring crops SB and SM which follow WW, the catch crop Mu is sown in combination with primary tillage in August after WW harvest. Additionally, nitrogen fertilization is carried out using 40 kg N ha^{-1} UAN (solution of urea and ammonium nitrate). Nitrogen fertilization for the main crops is performed using UAN depending on the amount identified as optimal for each particular year. Work performed at the field trial uses machinery typically employed in practice; special trial equipment is only used for sowing SB (three-row plot drill). SB are harvested using a six-row self-propelled SB harvester. The WW harvest is performed using a self-propelled combine harvester. A self-propelled forage harvester is used to harvest SM, with the harvested crop transferred onto a transport vehicle during operation.

2.2 Investigations into soil structure at the field trial Aiterhofen

After having completed the entire rotation on each plot, in May 2013, samples were taken from those plots with the first crop rotation field (Table III-1) of all crop rotations. The sampling was repeated in 2014 for the same crop rotation fields which were than cultivated on different plots, except the SM monoculture. The Sampling was conducted after the emergence of SB and SM. Undisturbed soil core samples (250 cm^3, height 6 cm, n = 4 per plot and depth) from soil depths 2-8 cm, 12-18 cm, 22-28 cm and 32-38 cm were saturated and then adjusted to a matrix potential of -6 kPa in a sand box in order to determine air capacity (AC) (ISO 11274:1998). Subsequently, the same soil cores were used to determine saturated hydraulic conductivity (k_S) in a stationary system (percolation time 4 h) (ICS 13.080:65.060.35).

2.3 Modelling the soil compaction risk

2.3.1 Model structure

The soil compaction risk is modelled based on the method by Rücknagel et al. (2015) and is performed using the modelling software REPRO (REPROduction of soil fertility, Hülsbergen, 2003). In this model, the soil strength (precompression stress σ_p) at two soil depths (lower topsoil at 20 cm and subsoil at 35 cm) is contrasted with the vertical soil stress (major principal stress σ_z) at the respective soil depth. Soil strength is adjusted depending on the water content (Rücknagel et al., 2012). If the vertical soil stress exceeds the soil strength of the soil structure, this results in a dimensionless Soil Compaction Index (SCI). The SCI reflects the soil compaction risk using the categories (i) low (SCI $\leq$ 0.10), (ii) medium (SCI 0.11-0.20); (iii) high (SCI 0.21-0.30), (iv) very high (SCI 0.31-0.40) and (v) extremely high (SCI > 0.40). The input parameters required are: (i) Technical specifications of the machinery used as well as (ii) the dates on which they were driven over the soil; (iii) mechanical precompression stress at both soil depths for a matrix potential of -6 kPa; (iv) soil water content.

The SCIs are first modelled annually for the single crop specific operations: (i) Tillage (comprises primary tillage, stubble tillage and seedbed preparation); (ii) seeding; (iii) fertilization (comprises N and P/K fertilization); (iv) pesticide application; (v) harvest; (vi) field transport during SM harvest. This serves to identify the level of the soil compaction risk for single operations in individual years. In a second step, the SCIs are modelled for entire crop rotations. For that, all operations performed each crop rotation plot in the reference period are sorted in descending order of their modelled SCI. Then, according to the proportion of wheeled area, these SCIs are summed until a proportion of 100 % wheeled area is reached. The maximum modelled SCIs for single operations, in combination with their proportion of wheeled area, are thus crucial to model the SCI for entire rotations. For a more detailed explanation see Rücknagel (2007) and Rücknagel et al. (2015).

2.3.2 Input parameters

2.3.2.1 Technical parameters and husbandry – model farm Aiterhofen

In order to validate the model (see chapter 2.3.3), the soil compaction risk is only modelled based on the equipment actually used in the field trial. However, not all of this equipment represents the current state of the art and SB is sown using special field trial equipment. Therefore, the estimation of the soil compaction risk of entire crop rotations is based on a model farm of 75 ha which is a typical size for the region. The technical equipment typically used in modern practice to manage the four crop rotations is set for a farm of this size. The cultivation dates from the field trial are used to model the soil compaction risk for each crop rotation plot in each year. The technical data required for modelling (axle load and tyres of the heaviest axle) are taken from the machines' respective operating manuals and are listed in Appendix 2 and Appendix 3. For harvesting WW and SB, it is assumed that the harvested crop is transferred to the transport vehicle or a beet storage clamp at the edge of the field. The parallel harvesting method is used for SM, with the SM forage transferred to the transport vehicle whilst driving. In the case of SB harvest, diagonal steer is assumed, where the wheels of the rear axle run next to the wheel tracks of the front axle. Depending on the actual axle loads, the tyre inflation pressures are adjusted to the lowest technically permissible pressures for field work conditions, although these are never below 0.8 bar. A full hopper is assumed for fertilization and the application of pesticides as well as for transporting the SM. Two scenarios are modelled for harvesting WW and SB. In the first scenario, the SCIs are modelled for a hopper that is 100 % full. In the second scenario, in years when SCIs > 0.10 were identified in the first scenario, the hopper load is reduced to 50 % and the tyre inflation pressure adjusted.

In order to obtain representative results for the soil compaction risks of the individual crop rotations, all operations performed on the crop rotation plots over a period of three rotations (2004 until 2012) are considered. Since cultivation dates from the field trial are available for the years 2010, 2011 and 2012 only, these dates are applied to the foregoing years. Using the first plot of crop rotation 2 (Mu_SB-WW-WW) as an example, Appendix 4 shows the operations performed in the field trial with the corresponding machinery or machinery combinations from the model farm. To estimate the soil compaction risk of one crop rotation plot, all operations following the harvest of the preceding crop until the harvest of the observed crop are taken into account.

2.3.2.2 Soil strength at -6 kPa matric potential

In the field trial, soil samples were taken in the year 2013 and used to determine the mechanical precompression stress using the method by Rücknagel et al. (2007), which is based on the ratio of aggregate density to dry bulk density. The precompression stress is log 1.91 (= 81.3 kPa) for the topsoil (20 cm) and log 1.86 (= 72.4 kPa) for the subsoil (35 cm), and is only included as a typical site specific value when modelling the soil compaction risk for the model farm.

2.3.2.3 Soil water content during wheeling

Soil water content (% field capacity - % FC) is modelled on a daily basis (period 2004 to 2012) by the German Meteorological Service (Deutscher Wetterdienst, DWD) for the 0-60 cm soil layer (Straubing station, texture silt loam, 38 vol% FC) and for the crops SB, SM and WW. Generally, for all three crop types, a decrease in soil water content can be observed as the vegetation period commences in the spring, and thus evapotranspiration increases until the respective crop is harvested (Figure III-1). In the period considered, soil water content levels at harvest vary considerably. At the time of harvest, the mean soil water content is 63 % FC for WW, 77 % FC for SM and 59 % FC for SB. However, the values vary between 35 and 85 % FC for WW, 44 and 97 % FC for SM and 41 to 79 % FC for SB depending on the respective year. After harvest and declining evapotranspiration in the autumn, the average soil water content increases up to field capacity until spring time for all crops.

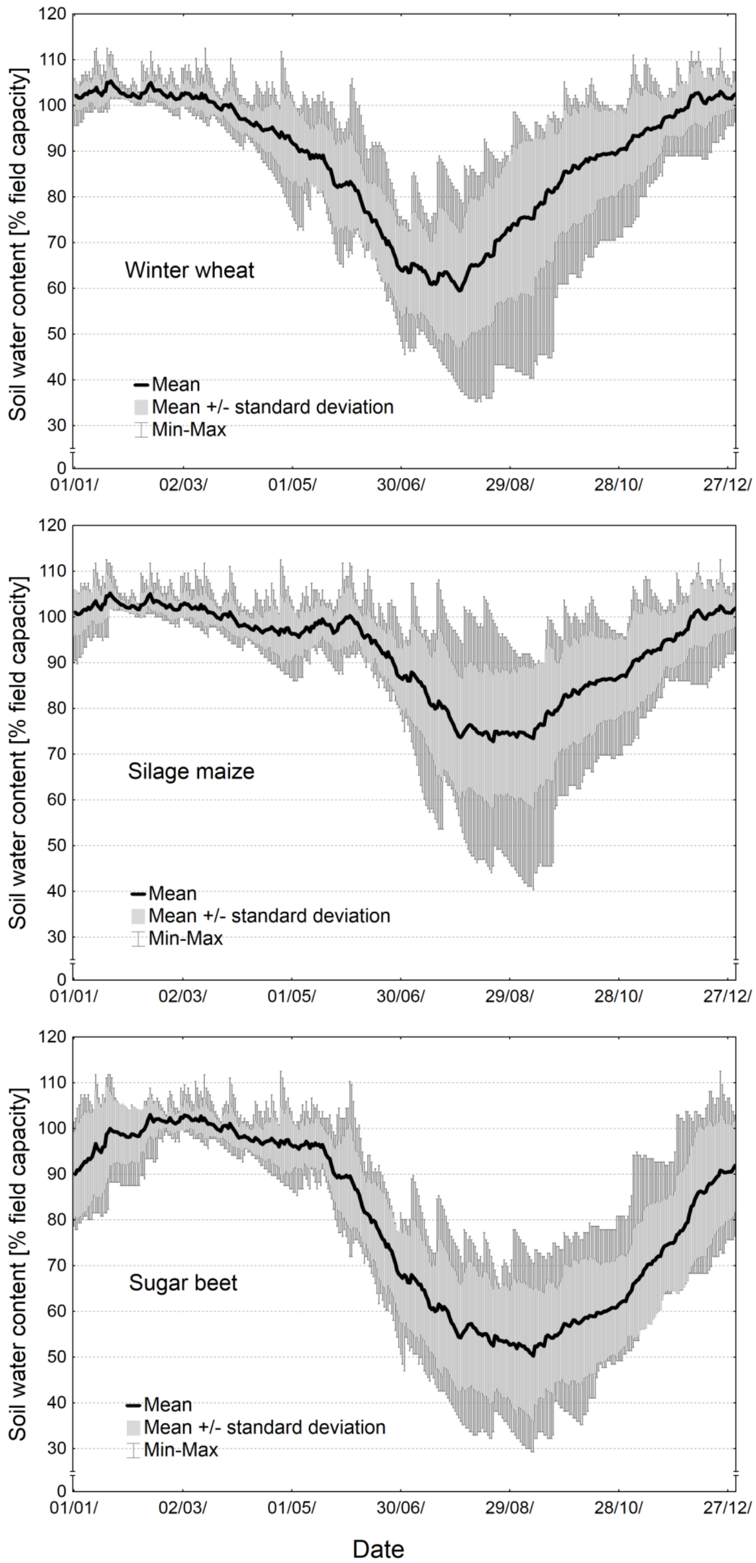

Figure III-1. Seasonal course and annual variation in soil water content for the crops investigated, modelled for the 0-60 cm soil depth by the German Meteorological Service (DWD, Straubing station, period 2004 to 2012).

2.3.3 Model validation

In order to test the validity of the model, the SCIs modelled for the crop rotations are compared with the actual changes in AC as a physical soil parameter. To this end, in the year 2013, soil cores (220 cm^3, h = 2.8 cm, n = 5) were taken from the soil depths 20 cm and 35 cm from an adjacent field whose soil structure was comparable to that of a ploughed topsoil and thus reflected the initial soil conditions before the field trial began. These soil cores were saturated and then adjusted to a matrix potential of -6 kPa in a sand box in order to determine AC according to ISO 11274:1998. After subsequent soil compression tests, Casagrande's (1936) graphical methods were used by two experts working independently of each other to determine the mechanical precompression stress (Rücknagel et al., 2010). This is log 1.58 (38.0 kPa) for the topsoil (20 cm) and log 1.72 (52.5 kPa) for the subsoil (35 cm). For validating the model, these latter values are used as initial values before the trial was set up. Based on the machinery used in reality during the field trial, the SCI is modelled for the areas of the plots which were sampled in 2013 and 2014. Therefore, operations involving driving along permanent traffic lanes, such as fertilizer and pesticide application, are not considered.

The change in AC is calculated based on the values from the trial plots and those from the adjacent field. The AC values at 20 cm in the adjacent field are compared to the trial plot values from 22-28 cm, and the AC values at 35 cm from the adjacent field against the trial plot values from 32-38 cm.

2.4 Statistical analysis

An analysis of variance is carried out using the program SAS (SAS Institute, 2008) 2008) in order to statistically evaluate the parameters AC and k_S. Prior to this, the data set for k_S was logarithmized and the data sets of the soil parameters k_S and AC were checked for normal distribution by a Shapiro-Wilk test with the program Statistica (Statsoft, 2014). A mixed statistical model is used, in which the effects crop rotation, year, crop rotation*year, replication and replication*block are recognised as fixed effects. The plots sampled in the respective years of the investigation and the soil cores per plot are included in the model as random effects and repeated measures. Thus, n = 16 values are allocated per crop rotation, sampling depth and year. The degrees of freedom are estimated according to Kenward and Roger (1997). An F-test is conducted to test the fixed effects for significance (α = 5 %) by using the SAS procedure MIXED.

Due to unbalanced data sets, the pairwise comparison of means (Tukey-Kramer method) is performed using adjusted means and the LS MEANS procedure.

The descriptive evaluation of soil compaction risks is performed using the Statistica software (Statsoft, 2014). Box-and-whisker plots serve to identify the soil compaction risk for the individual operations. The location parameter used is the median. The 25 % and 75 % percentiles as well as the minimum and maximum values indicate the spread and variation; the sample size is n = 9 years. In order to evaluate the soil compaction risk of the entire crop rotations, the median, minimum and maximum are provided. These values indicate the SCIs identified for the individual crop rotation plots of a crop rotation. The exception is SM monoculture, because this consists of just one plot and therefore only one value can be provided.

Validation is performed by correlating the SCIs identified for the field trial and the change in AC from the years 2013 and 2014 for both soil depths separately using the program Statistica (Statsoft, 2014). Thus, n = 8 pairs of values are calculated for each depth. Additional an F-test to test the effects soil depth, year and year*soil depth for significance (α = 5 %) is performed for both, the change in AC and the SCIs modelled, by using the SAS procedure GLM. Thus, n = 8 values are allocated per soil depth.

3 Results

3.1 Measured soil structure for the field trial Aiterhofen

The crop rotation has a significant impact on the soil structural properties in the topsoil (2-8 cm, Table III-2). For the parameter AC, the crop rotation*year interactions is significant at this soil depth, meaning the two sampling years are considered individually for the pairwise comparison of means. There are no significant interactions at the other soil depths (12-18, 22-28 and 32-38 cm) or for the parameter k_S (all soil depths). Therefore, sampling years are considered not individually for the pairwise comparison of means. In 2013, the crop rotation SB-WW-Mu_SM reveals a significantly lower AC value compared with the crop rotation Mu_SM-WW-WW while the rotations SM monoculture and Mu_SB-WW-WW are intermediate (Table III-3). In 2014, the differences between the variants are not significant. For the parameter k_S, the highest values are observed in the topsoil (2-8 cm) in variants where Mu is cultivated as a catch crop and WW as a preceding crop (Mu_SB-WW-WW, Mu_SM-WW-WW). This effect is statistically sound when compared with the SM monoculture. At the other soil depths, no considerable differences can be discerned between the different crop rotations for AC and k_S.

Table III-2. Probability values from F-test of fixed effects for the parameter air capacity (AC) and saturated hydraulic conductivity (k_S) at different soil depths at the field trial Aiterhofen (sampling years 2013 and 2014).

Effect	Soil depth [cm] 2-8	12-18	22-28	32-38
	Air capacity (AC)			
Crop rotation	0.014	0.359	0.156	0.332
Year	<0.001	0.362	0.876	0.862
Crop rotation*year	0.018	0.664	0.632	0.691
Replication	0.068	0.467	0.193	0.804
Replication*Block	0.572	0.811	0.211	0.579
	Saturated hydraulic conductivity (k_S)			
Crop rotation	0.001	0.657	0.094	0.513
Year	0.825	0.821	0.395	0.548
Crop rotation*year	0.400	0.854	0.464	0.802
Replication	0.090	0.693	0.162	0.507
Replication*Block	0.644	0.966	0.744	0.901

Table III-3. Crop rotation effects on air capacity (AC) and saturated hydraulic conductivity (k_S) at the field trial Aiterhofen (sampling years 2013 and 2014). Different lower-case letters show significant differences for $p \leq 0.05$ (Mu - mustard catch crop, SB - sugar beet, SM - silage maize, WW - winter wheat).

Parameter	Soil depth [cm]	Crop rotation SM	Mu_SB-WW-WW	Mu_SM-WW-WW	SB-WW-Mu_SM
AC [vol%]	2-8[a] *2013*	24.6 *ab*	22.8 a*b*	26.5 *a*	18.6 *b*
	2-8[a] *2014*	18.7	16.8	20.1	19.6
	12-18[b]	13.6	10.7	12.3	11.0
	22-28[b]	9.2	10.6	10.7	8.4
	32-38[b]	6.2	6.7	8.2	6.9
k_S [cm d^{-1}]	2-8[b]	67 *a*	240 *b*	196 *b*	108 *ab*
	12-18[b]	52	33	64	36
	22-28[b]	25	42	74	20
	32-38[b]	11	19	36	23

[a] both sampling years separated, as significant Crop rotation * Year interaction present

[b] means across both sampling years, as no significant Crop rotation * Year interactions present

3.2 Soil compaction risk modelled for the model farm Aiterhofen

3.2.1 Model validation

For the modelled SCIs and the change in AC at the respective soil depth, the range of values is small. Thus, there are no significant correlations between these parameters (20 cm: r = 0.41, p = 0.32; 35 cm: r = -0.06, p = 0.89). However, the changes in AC for the topsoil (20 cm) are significantly higher than those for the subsoil (35 cm), as well as the modelled SCIs for the topsoil are significantly higher than those for the subsoil (35 cm) (Figure III-2). Therefore, greater differences in the level of soil compaction, in terms of changes in AC, can be detected by the modelled SCIs.

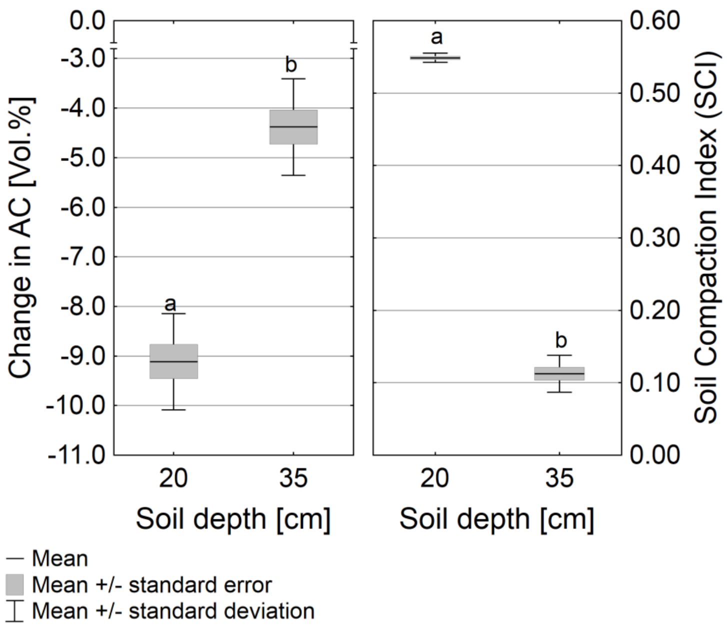

Figure III-2. Box-plots of the change in air capacity (AC) and the modelled Soil Compaction Index for two soil depths at the field trial Aiterhofen (sampling years 2013 and 2014). Different lower-case letters show significant differences for $p \leq 0.05$ (n = 8).

3.2.2 Soil Compaction Index for crop-specific operations

In the lower topsoil (20 cm), the medians of the modelled SCIs are below 0.10 for all crop-specific operations (Figure III-3). The soil compaction risk can therefore be classified as low. However, far higher SCIs, and thus higher soil compaction risks, can be observed in individual years: For example, in the observation period, the SB and WW harvesting methods result in the highest SCIs and very high soil compaction risks. Further, the fertilizer application is associated with high soil compaction risks, regardless of the cultivated crop. Using the forage harvester for SM harvest showed either a small soil compaction risk or none at all.

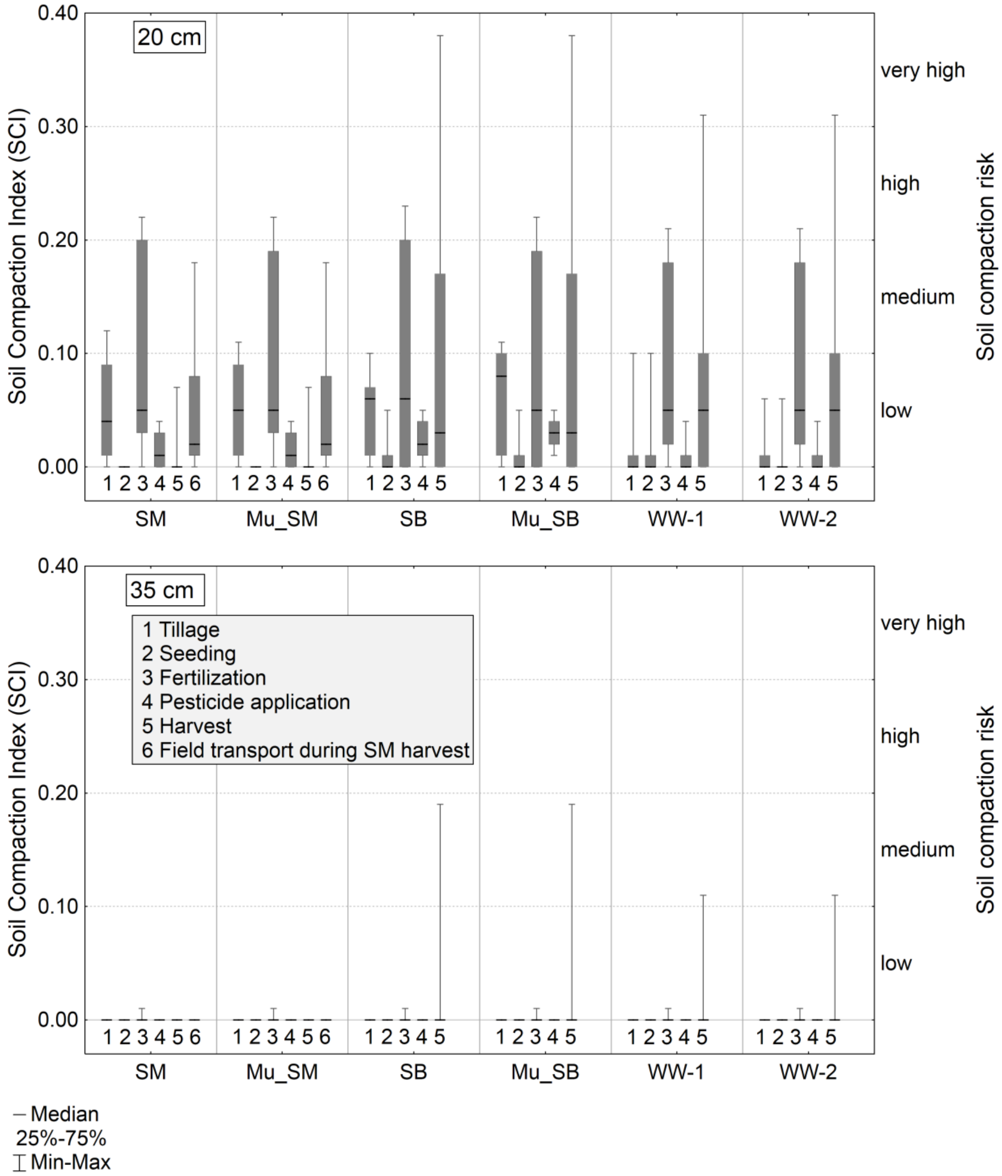

Figure III-3. Box-plot of the modelled Soil Compaction Index (SCI) and the respective soil compaction risk modelled annually for each crop-specific operation conducted for the weather conditions of 2004-2012 at two soil depths (20 and 35 cm) for the model farm Aiterhofen. 'Tillage' comprises the operations primary tillage, stubble cultivation and seedbed preparation. 'Fertilization' comprises the operations N and P/K fertilization (SB – sugar beet; SM – silage maize, Mu – mustard catch crop, WW – winter wheat).

However, the field transport of SM during harvest leads to medium soil compaction risks in individual years. The maximum modelled SCIs determined for tillage, sowing and pesticide application operations are far lower than for the harvesting methods and fertilization. For the spring crops SM, Mu_SM, SB and Mu_SB, the soil compaction risks of the operations involving soil tillage and the application of pesticides are higher than for the WW crop rotation fields. Sowing generally has a minor influence or none at all (SM cultivation) on the soil compaction risk.

In the subsoil (35 cm), an SCI > 0.00 is only present in individual years. Here, SB harvest displays the highest soil compaction risks, which are classified as "medium", followed by WW harvest and fertilization. The other operations result in low or no soil compaction risk at this soil depth. At both soil depths, halving the hopper load and adjusting the tyre inflation pressure during WW and SB harvest reduces the maximum modelled SCI (Figure III-4). In accordance with the classification of the modelled SCI, for the SB harvest the maximum soil compaction risk drops from very high to high (20 cm) and from medium to low (35 cm), and for the WW harvest from very high to medium (20 cm) and from medium to low (35 cm).

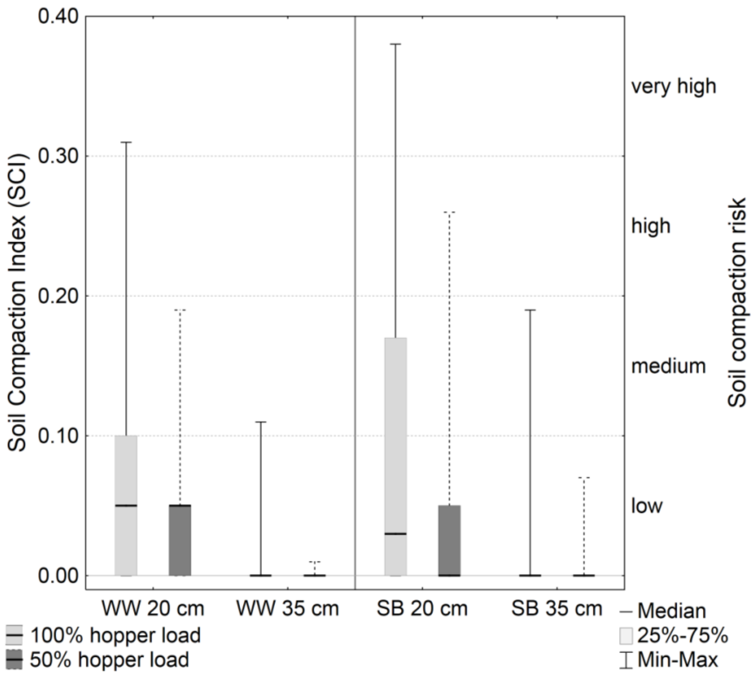

Figure III-4. Modelled Soil Compaction Index (SCI) and the respective soil compaction risk conducted for the weather conditions of 2004-2012 at two soil depths (20 and 35 cm) for the harvesting of sugar beet (SB) and winter wheat (WW) with reduced hopper load and adjusted tyre inflation pressure for those years in which an SCI > 0.10 is indicated for hopper load of 100 % (n = 9) (model farm Aiterhofen).

3.2.3 Soil compaction risk of entire crop rotations

Across the whole period of 9 years, both, the highest soil compaction risks and the highest variation exist for the crop rotations including SB (Mu_SB-WW-WW, SB-WW_SM) (Figure III-5). Reducing the hopper load at SB and WW harvest and adjusting the tyre inflation pressure reduces the soil compaction risk at both soil depths. At both soil depths and for both hopper loads, the differences between the crop rotations including SB are very small, although the crop rotations Mu_SB-WW-WW and SB-WW-Mu_SM vary in terms of their proportions of WW and SM cultivation.

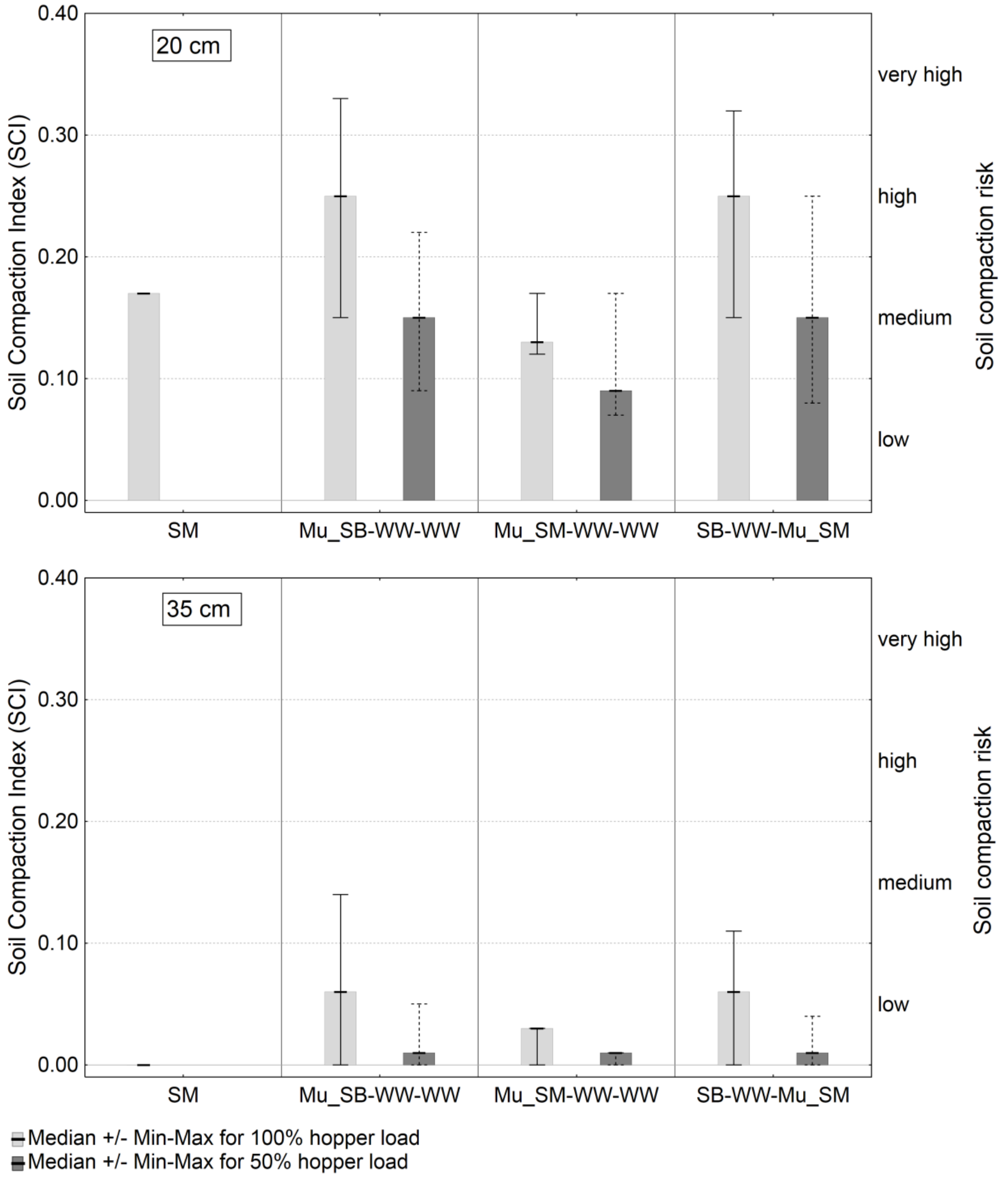

Figure III-5. Modelled Soil compaction Index (SCI) and the respective soil compaction risk for entire crop rotations conducted for the weather conditions of 2004-2012 at two soil depths (20 and 35 cm) for the model farm Aiterhofen (SB – sugar beet, SM – silage maize, Mu – mustard, WW – winter wheat).

Compared to SM in monoculture, cultivating SM in crop rotations with twofold WW (Mu_SM-WW-WW) reduces the soil compaction risk in the lower topsoil (20 cm) only (Fig. 5). In the subsoil (35 cm), there are no soil compaction risks for SM monoculture, while Mu_SM-WW-WW displays no to low soil compaction risks. These can thus be attributed to the low to medium soil compaction risk when harvesting WW. In crop rotations with WW and SB, the soil compaction risk can be reduced by halving the hopper load and adjusting the tyre inflation pressure during harvest.

4 Discussion

4.1 Soil structure measured at the field trial Aiterhofen

In the literature, threshold values for a functioning soil structure are specified as 8 vol% AC and 10 cm d^{-1} k_S in the topsoil as well as 5 vol% AC and 10 cm d^{-1} k_S in the subsoil (Werner and Paul, 1999; Lebert et al., 2004). The values in this investigation do not drop below these thresholds, and as such the physical soil parameters studied do not suggest a functional restriction of soil structure at any soil depth or for any crop rotation.

The differences in soil structure found in this trial are restricted to the topsoil (2-8 cm). At this depth, for the parameter AC the only significant effect of the crop rotation is a reduction in 2013 in the SB-WW-Mu_SM rotation compared to Mu_SM-WW-WW. After SM was cultivated as a preceding crop, the soil probably became compacted and, when preparing the seed-bed for the following SM in the SM monoculture, it was loosened more than for SB. There was a higher soil compaction risk when harvesting SM compared to WW in 2012. For the equipment used in the field trial the estimated SCI for the forage harvester during SM harvest was 0.54 while the SCI for WW harvest was 0.00 (data not shown). This means that the investigations into soil structure in 2013 would presumably show lower AC in all plots with SM as a preceding crop. However, in 2013, the soil under SB cultivated after SM as a preceding crop, tends to higher ACs than under SM monoculture. This is due to the fact that SM seedbed preparation is performed using a rotary harrow at a soil depth of 10 cm, while for SB only a shallow seedbed (< 5 cm) is prepared using a cultivator.

With regard to the parameter k_S, the differences are probably influenced by the combination of preceding crops. The higher k_S values in the topsoil (2-8 cm) of the variants where Mu is cultivated as a catch crop and WW as a preceding crop (Mu_SB-WW-WW, Mu-SM-WW-WW) may be the result of improved structural and aggregate stability, and in turn the reduced susceptibility to surface capping. In situations where WW harvest residues are left on the soil surface, as in our trial, aggregate stability and the water infiltration rate of the soil increase (Ghuman and Sur, 2001). Also, cultivating catch crops under reduced tillage can result in higher macroporosity in the topsoil (Głąb and Kulig, 2008), which contributes heavily to k_S (Beven and Germann, 1982).

At the other soil depths, there are only minor differences in soil structure or none at all. Unfavourable soil structure conditions are especially critical in the subsoil, as it is costly to rectify such problems and they are often persistent (Alakukku, 1996). Subsoil compaction is usually only observed if soils are subjected to stress from high wheel loads when their water content is high or, additionally, if the frequency of wheeling increases (Koch et al., 2008). However, the machinery used in the trial investigated is unlikely to cause compaction of this extent. Furthermore, crop-related loosening of the soil structure in the topsoil is often only observed in crops with strong taproot systems, such as alfalfa (*Medicago* ssp.) (Oquist et al., 2006; Uteau et al., 2013), and is unlikely to occur with the crops investigated here.

4.2 Soil compaction risk modelled for the model farm Aiterhofen

A number of models are described which serve to predict the soil compaction risk (O'Sullivan et al., 1999; Horn and Fleige, 2003; van den Akker, 2004; Keller et al., 2007). These models can be used to estimate and depict the site-related soil compaction risk (van den Akker and Hoogland, 2011; D'Or and Destain, 2014), for individual machinery passes or operations (Arvidsson et al., 2003; Défossez et al., 2003; Trautner and Arvidsson, 2003; Lozano et al., 2013), or for a combination of both (Duttmann et al., 2014). Compared to these models, the model used here can quantify and assess the soil compaction risk of entire crop rotations up to the farm level. The model can be integrated into the software REPRO, making all necessary input parameters available. For example, this means that the soil compaction risks and greenhouse gas or energy balances can be modelled on the basis of the same farm machinery. By using the standardisation function presented by Rücknagel et al. (2015), it is possible to incorporate this information into sustainability assessments of farming systems.

Rücknagel et al. (2015) validated the model based on measurements of dry bulk density and k_S. Like the results presented, Rücknagel et al. (2015) found that the modelled SCIs and changes in dry bulk density are lower for the subsoil (35 cm) than for the lower topsoil (20 cm). In this trial, for the soil depths 22-28 cm and 32-38 cm, which are used to validate the model, there are only slight differences in soil structure between crop rotations measured. Similarly, the crop rotation SCIs modelled for the trial-specific machinery differ only marginally. When differences in the modelled SCIs increases, as it is for the subsoil (35 cm) comparing to the topsoil (20 cm), higher changes in AC are measured. Thus, the model delivers valid results for the Aiterhofen site.

Models represent a simplified version of reality, and as such they all have limitations. The soil water contents included for modelling in this study are for the soil depth 0-60 cm and not considered individually for both soil depths (20 cm, 35 cm) evaluated. Spatial and temporal variability of soil water content in fields are possible. Furthermore, applying the cultivation dates from the field trial to previous years is associated with inaccuracies in terms of the cultivation dates and the respective soil water content. There are no real cultivation dates for the years 2004 to 2009, because the field trial was not set up before 2010. However, a longer period needs to be considered to ensure representative modelling of the soil compaction risk. Another limitation of the model is that it assumes static hopper load levels for sowing, pesticides, fertilization, SB and WW harvest and SM transport. So, the modelled SCI – and the soil compaction risk – only apply to the part of the field driven over with a full hopper load (or with half a hopper load for the second scenario). However, in order to identify machinery and/or operations which pose high soil compaction risks, the maximum possible axle load must be used, since this condition also occurs in practice even if for small areas only.

The results of modelling the soil compaction risks for individual operations and for the entire crop rotations are in keeping with past studies. Based on the contact pressure, the proportion of area driven over and the product of the wheel load and the distance travelled, Chamen et al. (1992) ascribe a high soil compaction risk to the operations of soil tillage and harvest in the case of root and forage crops, like SB and SM. Even so, it is possible to reduce the soil compaction risk by sowing SB and SM later and harvesting them earlier, when soil water contents are usually lower (Boizard et al., 2002; Capowiez et al., 2009). As water content increases, the soil's compactability also increases

(Rücknagel et al., 2012), and the risk of causing soil compaction, even at greater soil depths, increases.

Accordingly, operations involving driving over soils with high axle loads at times when soil water content is high, display a high soil compaction risk. When comparing entire crop rotations, the model uses all operations in the period considered of 9 years to model the SCI. Therefore, high modelled SCIs which only appear in one year have an impact on the soil compaction risk of the entire period considered. In the investigations presented, this applies mainly to the harvesting operations. While it is true that, taking the annual average, soil water contents at the time of harvest are far below those when fertilizing in the spring, in individual years soil water contents which are approximately 20 % FC above the average for the period considered are observed for all three crops. In such years, there are two reasons why the harvesting operations have a high soil compaction risk. Firstly, the axle loads are very high for WW and SB harvest, particularly when the hopper is full. Secondly, the working width is very small. In the case of SB harvest, for example, it was 3 m and when using diagonal steer, as in the model assumptions, the wheels of the rear axle run next to the wheel tracks of the front axle. Thus, almost the entire area is driven over.

Tillage operations for the spring crops SM and SB display a greater soil compaction risk than for WW. So far, more unfavourable soil structure conditions have been found when cultivating SB and SM compared to WW (Jacobs et al., 2014), after cultivating spring crops compared to winter rape and winter cereals as preceding crops (Götze et al., 2013) and in crop rotations with a higher proportion of spring crops (Boizard et al., 2002; Capowiez et al., 2009). The authors attribute these findings in part to higher soil compaction risks during tillage and spring crop cultivation.

The results presented also show that, in years with an increased soil compaction risk, halving the hopper load and respective reduction of tire inflation pressure during the SB and WW harvest decreases soil compaction risks. In Germany, this approach is recommended as part of ‘good agricultural practice’ as a practical, weather-adjusted strategy of preventive soil protection when harvesting SB (Brunotte et al., 2013). However, this does require that the field lengths are sized accordingly so that the hopper load does not exceed 50 % at the end of the field. When harvesting SB, halving the hopper load reduces the axle load by around 20 %, and decreasing the tyre inflation pressure from 2.7 bar to 2.0 bar is technically acceptable. This reduces contact pressure (Koolen et al.,

1992) and the propagation of pressure at greater depths (Söhne, 1953), and the soil compaction risk decreases both for the lower topsoil (20 cm) and for the subsoil (35 cm).

5 Conclusions

Under the experimental conditions at the field trial, following a complete rotation there are no differences in soil structure as a result of SM or SB cultivation. Cultivating WW and Mu as preceding crops for SB and SM increases k_S (196 cm d^{-1} to 240 cm d^{-1}) compared to SM as a preceding crop (67 cm d^{-1} to 108 cm d^{-1}), indicating better structural stability and infiltration capacity, and should therefore be preferred. To assess the soil compaction risks of entire crop rotations, it is necessary to distinguish between soil depths. If the intention is to permanently refrain from loosening the topsoil in a cropping system (no-till or minimum tillage), the soil compaction risk at a soil depth of 20 cm is decisive for the choice of cropping system. For the model conditions, cultivating SM (medium soil compaction risks) will presumably lead to less adverse effects in the soil structure at 20 cm depth compared to SB (medium to very high soil compaction risks). Even when the topsoil is loosened, the soil compaction risk at a soil depth of 35 cm is crucial for the evaluation. Compaction in this depth cannot be rectified, or doing so is highly costly, and as such any compaction should be avoided. Provided that the hopper load is halved and the tyre inflation pressure is adjusted in years with a high soil compaction risk when harvesting SB and WW, there are only slight differences in the subsoil (35 cm) between the variants. Under these circumstances, the crop rotations investigated caused no to low soil compaction risks and are therefore not associated with environmental impacts caused by soil compaction.

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IV Crop rotation effects on yield, technological quality and yield stability of sugar beet after 45 trial years

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Abstract

Long-term field trials constitute an essential basis for research into the effects of agricultural management practices on yield and soil properties. The long-term field trial Etzdorf (Germany) was set up in 1970 and uses various crop rotations with sugar beets (*Beta vulgaris* L., SB) to investigate the influence of increasing cropping concentrations (20 % to 100 %) and decreasing cropping intervals (0 to 4 years) on the yield and quality parameters of SB. However, evaluation of the yield stability of SB in diverse crop rotations has not been conducted in this context so far. For this reason, the yield for the last 13 years of the trial (2002 until 2014) was subjected to such an evaluation. Besides cropping interval and cropping concentration, the crop rotations investigated also differed in terms of the complementary crops cultivated (winter wheat, *Triticum aestivum* L.; alfalfa, *Medicago ssp.*; potato, *Solanum tuberosum L.* and grain maize, *Zea mays* L.). Both SB root yield and white sugar yield increased with an increasing cropping interval or decreasing cropping concentration of SB in the crop rotation. In addition, a positive effect on root yield and white sugar yield was seen when integrating alfalfa, while cultivating SB after SB displayed the lowest root yield and white sugar yield. Sugar content was lowest in SB monoculture. In order to assess stability of white sugar yield, the coefficient of variation and ecovalence were calculated, and a linear regression analysis of the individual crop rotations' annual yield was performed for the annual average of all crop rotations. When considering these three parameters, the crop rotations with a cropping interval of at least 2 years displayed higher yield stability, with simultaneously higher white sugar yield, than the crop rotations with a cropping interval of 0 and 1 year. By integrating alfalfa into the crop rotation, it was also possible to achieve above-average white sugar yield with high yield stability for a cropping interval of 1 year.

1 Introduction

In the context of crop rotation, sugar beet (SB, *Beta vulgaris L.*) is characterised by a marked yield loss if cultivated in narrow crop rotation or continuously (monoculture). This is caused mainly by infestation with the beet cyst nematode *Heterodera schachtii* Schmidt (Liste et al., 1992) or soil-borne diseases such as black root (*Aphanomyces cochlioides* Drechsler, Schäufele and Winner, 1989). Increasing proportions of SB in the crop rotation up to monoculture therefore usually lead to significant yield losses (Deumelandt et al., 2010; Hlisnikovsky et al., 2014). Whereas, also steady SB yield in monoculture compared to crop rotations was reported by Draycott et al. (1978). On farms growing SB, approximately 10 % to 25 % of arable land is therefore cultivated with SB (Stockfisch et al., 2008). But this does not allow any precise conclusions to be drawn about cropping concentrations within crop rotations. Following Märländer et al. (2003), SB is included in the crop rotation every 3 to 4 years. For the southern German cultivation area, Graber and Risser (2013) report that 33 % of SB is cultivated with a cropping interval of 2 years, 26 % with 3 years and 40 % with 4 or more years. Cropping intervals of less than 2 years are therefore uncommon for SB. The primary preceding crops grown before SB are winter wheat (WW, *Triticum aestivum* L.) and winter barley (*Hordeum vulgare* L.) (Buhre et al., 2014). In some regions, potatoes (*Solanum tuberosum* L.) and maize (*Zea mays* L.) are also increasingly being included as part of crop rotations (Märländer et al., 2003; Buhre et al., 2014). At present, also energy crop rotations with a high proportion of SB and maize for biomass production are discussed (Jacobs et al., 2014; Brauer-Siebrecht et al., 2016).

In the future, however, an increase in cropping concentrations of SB in crop rotations, or the increased cultivation of SB in short, 3- to 4-year crop rotations (cropping interval of 2 or 3 years) is likely. The abolition of the European quota system for sugar in 2017 (European Union, 2013) should see an overall rise in SB and sugar production across the EU member states of around 4 %, with the largest increases in Denmark, Germany, the United Kingdom and Romania (Burrell et al., 2014). Actually, the contract offers of sugar industry for the cultivation area may result in an increase of even more than one third in classical growing areas near sugar factories (Anonymus, 2016). An increased demand for SB will be covered by extending acreage in existing SB cultivation areas (Gocht et al., 2012), and SB production will continue to be concentrated near sugar factories in order to minimise transportation costs (Isermeyer et al., 2005). This could lead to a specialisation of farms growing SB, and as such a higher SB cropping concentration may also be economically advantageous even if yield is lower. However, one prerequisite for this is that yield remains stable when cropping concentration increases. So far yield stability analysis for SB has been limited to comparing varieties under differentiated environmental conditions (Liovic and Kristek, 2000; Hoffmann et al., 2009). Only a few studies have been performed with regard to agricultural management practices such as tillage or crop rotation variants (e.g. SB-WW-WW, catch crop_SB-WW-catch crop_WW, Heyland and Hambüchen, 1990).

The question therefore arises of how increased cropping concentrations of SB in the crop rotation, or reduced cropping intervals for SB, influence yield stability. In order to be able to map the impact of agricultural management practices on yield level, long-term field trials are necessary (Körschens, 2006, 2010). Furthermore, long-term field trials are a core element of basic agricultural research, and thus are necessary to investigate site-adapted management methods (Stützel et al., 2014). However, the number of long-term field trials in Europe has decreased during the last decades. The long-term field trial in Etzdorf was set up in 1970 in a traditional SB cultivation area in Germany and contains various crop rotations with increasing SB cropping concentrations. Despite its unique conception, the trial had to be stopped in 2015 because of technical and financial reasons. SB yield has been evaluated on a regular basis over the trial period (Fischer and Liste, 1979; Liste et al., 1992; Deumelandt et al., 2010), whereas the impact of crop rotations on the yield stability of SB has yet to be examined in detail. In the context of yield evaluations from the last 13 years, this paper therefore aims to demonstrate the yield stability of SB in crop rotations with different cropping concentrations and cropping intervals.

2 Material and methods

2.1 Field site and experimental design

The investigations were performed at a long-term field trial in Etzdorf (Saxony-Anhalt, Germany, 51°43' N; 11°76' E, altitude 134 m), which was started in 1970 and is run by the Martin Luther University Halle-Wittenberg. The soil type is classified as a Haplic Chernozem (FAO, 2006b). The soil texture in the tilled soil (0-30 cm) was that of a silt loam (250 g kg^{-1} clay, 50 g kg^{-1} sand), while the pH value was 6.9. The long-term (1970 to 2001) mean annual precipitation rate was 453 mm, and mean annual temperature was

9.0°C. For the reference period (2002 to 2014), the mean annual precipitation amounted to 506 mm (min. 350 mm, max. 663 mm), and the mean annual temperature was 9.3°C (min. 7.6°C, max. 10.4°C, Figure IV-1).

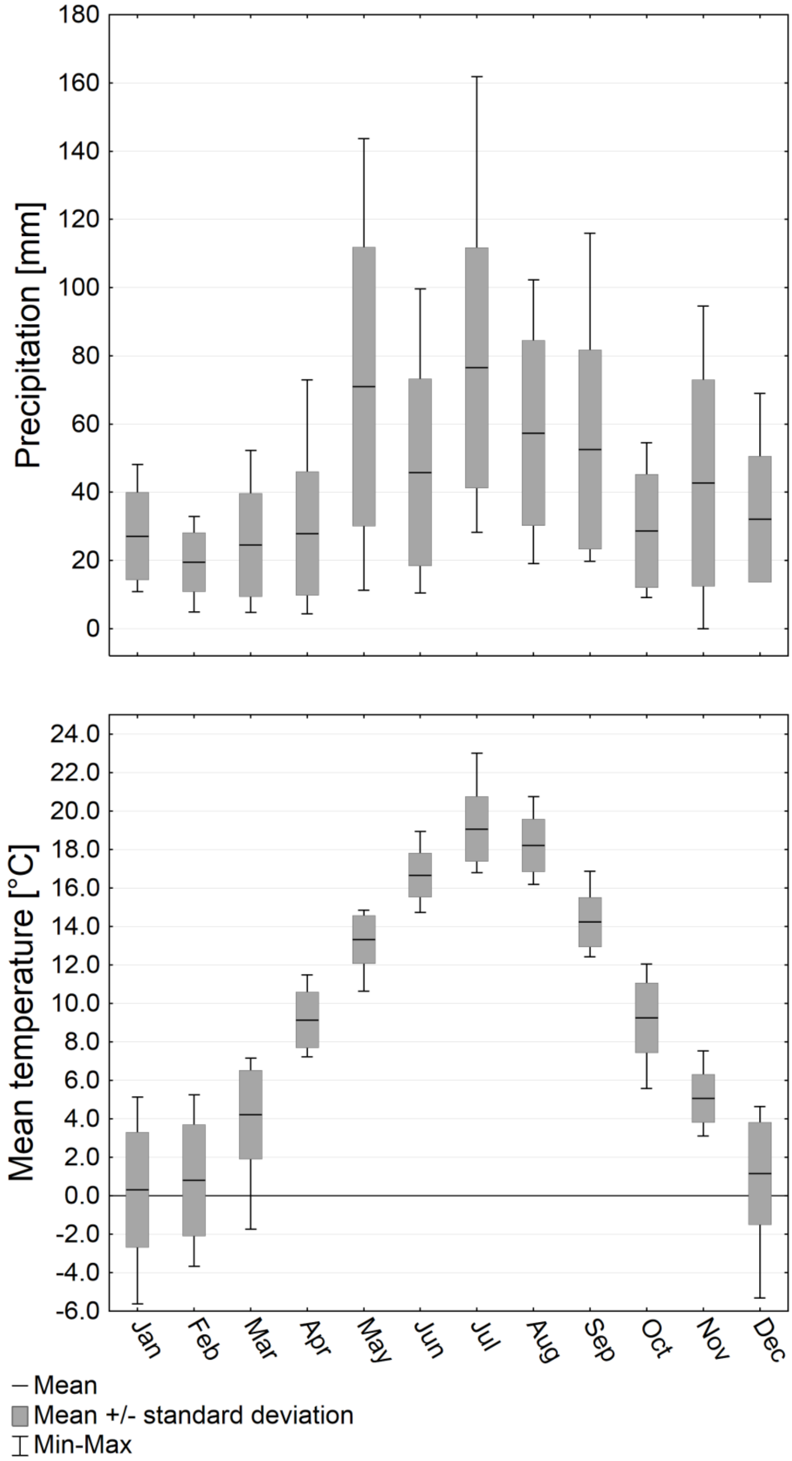

Figure IV-1. Mean precipitation rate and mean temperature by month for the period 2002-2014 at the long-term field trial Etzdorf.

Eight crop rotations were cultivated at the long-term field trial Etzdorf (Table IV-1). The crop rotations differed with regard to the cropping concentration of SB, the cropping interval for SB and the integration of winter wheat (WW, *Triticum aestivum L.*), grain maize (GM, *Zea mays L.*), potato (Pot, *Solanum tuberosum* L.) and alfalfa (Alf, *Medicago ssp*). Each crop rotation field was cultivated every year. For the crop rotations consisting of two or three crop rotation fields with SB (crop rotation 2, 5 and 6, Table IV-1), all crop rotation fields with SB were analysed separately, meaning twelve crop rotation fields were compared.

Table IV-1. Crop rotations at the long-term field trial Etzdorf (SB - sugar beet; WW - winter wheat; GM - grain maize, Pot - potato, Alf - alfalfa).

Crop rotation		Separate crop rotation fields with SB (preceding crop combination in brackets)	Cropping interval for SB [years]	Cropping concentration for SB [%]
1	SB-WW-Alf-WW	(WW-Alf-WW)-SB	3	25
2	SB-SB-WW-WW	(SB-WW-WW)-SB	2	50
		(WW-WW-SB)-SB	0	50
3	SB-Pot-WW	(Pot-WW)-SB	2	33
4	SB-WW-Alf-Alf-WW	(WW-Alf-Alf-WW)-SB	4	20
5	SB-SB-SB-WW	(SB-SB-WW)-SB	1	75
		(SB-WW-SB)-SB	0	75
		(WW-SB-SB)-SB	0	75
6	SB-WW-SB-Alf-WW	(WW-SB-Alf-WW)-SB	2	40
		(Alf-WW-SB-WW)-SB	1	40
7	SB-GM	(GM)-SB	1	50
8	SB monoculture	SB monoculture	0	100

The field trial had a block design with two replications (plot size 26.4 m², 8.8 m x 3.0 m). Resulting crop residues (SB and Pot leaves, WW and GM straw) were removed from the plots. Alf was cultivated as a forage crop and was usually harvested three times a year. Primary soil tillage was performed for the whole field trial in the autumn using a mouldboard plough at a soil depth of 30 cm. Mineral nitrogen fertilization was performed using 160 kg N ha^{-1} on SB, GM and Pot, while the amount used on WW depended on the requirements calculated for the current year (range 180 - 270 kg N ha^{-1}). Alf was not fertilized by mineral nitrogen. A uniform fertilization of P (58 kg ha^{-1}) and K (220 kg ha^{-1}) was performed to ensure a sufficient nutrient supply. The P content in the soil (0-30 cm soil depth) ranged from 29.9 to 37.6 mg 100 g^{-1} and K content ranged from 21.0 to 28.4 mg 100 g^{-1} (Deumelandt et al., 2010). The years 2002-2014 were used for the studies presented here, because the variety "Mosaik" was consistent cultivated for this period.

2.2 Yield and technological quality of sugar beet

The criteria of yield and technological quality applied in Germany for SB and their calculations are shown in equations IV-1 to IV-3 (Märländer et al., 2003). The root yield of SB and the white sugar yield were used as yield parameters. Calculation of the standard molasses loss (eq. IV-3) was performed in accordance with Buchholz et al. (1995) including a standard factory loss. A representative beet brei sample was used to identify the internal quality parameters of the SB. The beet brei was clarified using an aluminium sulphate solution. The filtrates were analysed for potassium (K) and sodium (Na) by flame photometry (ICUMSA 2007b) and for sugar content by polarization (ICUMSA 1994). Amino nitrogen (aminoN) was determined by the fluorimetric method (ICUMSA 2007a).

$$White\ sugar\ yield\ [t\ ha^{-1}] = white\ sugar\ content\ [\%] \times SB\ root\ yield\ [t\ ha^{-1}] \qquad \text{IV-1}$$

$$White\ sugar\ content\ [\%] = sugar\ content\ [\%] - standard\ molasses\ loss\ [\%] \qquad \text{IV-2}$$

$$Standard\ molasses\ loss\ [\%] = 0.12 \times (K + Na) + 0.24 \times aminoN + 1.08 \qquad \text{IV-3}$$

[K, Na and aminoN in mmol $(100g)^{-1}$ beet]

2.3 Statistical analysis

2.3.1 Yield and technological quality parameter analysis

An analysis of variance was carried out using the program SAS (SAS Institute, 2012) in order to statistically evaluate the effect of the crop rotation field on root yield, white sugar yield, white sugar content, sugar content, potassium, sodium, aminoN and standard molasses loss. Prior to this, the data sets of the yield parameters were checked for normal distribution by conducting a Shapiro-Wilk test with the program Statistica (Statsoft, 2014). The data sets for aminoN and standard molasses loss were not normally distributed and therefore logarithmized for an analysis of variance. A linear mixed model was used, in which the effects crop rotation field, year and crop rotation field*year were recognised as fixed and block as a random effect. Thus n = 2 values were allocated per crop rotation field and year. An F-test was conducted to test the fixed effects for significance (α = 5 %) by using the SAS procedure MIXED. The Tukey-Kramer method was used to adjust the p-values for the differences of the least-squares means for multiple testing.

2.3.2 Yield stability analysis

Stability analysis was conducted for the parameter white sugar yield for all SB crop rotation fields. This involved calculating the parameters coefficient of variation (eq. IV-4, Francis and Kannenberg, 1978, described by Piepho, 1998) and ecovalence according to Wricke (1962) (eq. IV-5).

$$CV_i = \frac{\sqrt{\sigma_{ii}}}{\mu_i}\ ;\ CV\% = CV_i * 100 \qquad \text{IV-4}$$

CV_i = coefficient of variation of the ith crop rotation field
$\sqrt{\sigma_{ii}}$ = variance of the white sugar yield of the ith crop rotation field
μ_i = mean white sugar yield of the ith crop rotation field

$$W_i = \sum_{i=1}^{J}\left(y_{ij} - \overline{y_{i\bullet}} - \overline{y_{\bullet j}} + \overline{y_{\bullet\bullet}}\right)^2 \qquad \text{IV-5}$$

W_i = ecovalence of the ith crop rotation field
y_{ij} = white sugar yield of the ith crop rotation field in the jth year
$\overline{y_{i\bullet}}$ = mean white sugar yield of the ith crop rotation field for all years
$\overline{y_{\bullet j}}$ = mean white sugar yield of the jth year for all crop rotation fields
$\overline{y_{\bullet\bullet}}$ = mean white sugar yield of all crop rotation fields for all years

The lower the coefficient of variation and ecovalence, the more stable the white sugar yield of a crop rotation field. Crop rotation fields which combine high white sugar yield with high yield stability are advantageous. Following Francis and Kannenberg (1978) and Graß et al. (2013), the coefficient of variation and ecovalence of a crop rotation field were plotted against the white sugar yield as a measure of yield stability.

In addition, linear regression analysis of the average white sugar yield of the individual crop rotation fields in one year were conducted for the average white sugar yield of all variants from one year, following the approach by Finlay and Wilkinson (1963) and Eberhart and Russell (1966) (eq. IV-6) with the procedure REG in SAS (SAS Institute, 2012).

$$Y_{ij} = \mu_i + \beta_i I_j + \delta_{ij} \qquad \text{IV-6}$$

Y_{ij} = white sugar yield of the i^{th} crop rotation field in the j^{th} year
μ_i = mean of the i^{th} crop rotation field for all years
β_i = regression coefficient for the i^{th} crop rotation field, slope of the regression line
δ_{ij} = deviation from regression line
I_j= environmental index (mean of all crop rotations at the j^{th} year)

Crop rotation fields with an estimated slope b = 1 have an average sensitivity to environmental conditions (Piepho, 1998). Crop rotation fields with b > 1 respond to improved environmental conditions with above-average white sugar yield growth. Crop rotation fields with b < 1 respond to improved environmental conditions with below-average white sugar yield growth. According to Eberhart and Russell (1966), yield stability is highest when slope b=1 and the deviation from the regression line is as small as possible. Therefore, the test option within the REG procedure was used to test if the slope is different from 1. The root mean square error (RMSE) and its coefficient of variation (RMSE proportion of average white sugar yield in %) were calculated as a measure of deviation from the regression line.

3 Results

3.1 Yield and technological quality of sugar beet

3.1.1 Root yield of sugar beet

Both crop rotation field and year influenced the root yield significantly (Table IV-2). There were no significant crop rotation field*year interactions, meaning a pairwise comparison of the crop rotation fields' average yield across all study years was possible. Here, increasing root yield was observed as the cropping interval increased (Figure IV-2). All crop rotation fields with SB as a preceding crop (cropping interval 0 years) displayed significantly lower root yield than SB crop rotation fields with a cropping interval of at least 1 year. Crop rotation fields with a cropping interval of 1 and 2 years and no integration of Alf in the crop rotation caused significantly lower root yield compared to crop rotation fields with 3 and 4 years. For the crop rotation fields including Alf, also an increase in root yield was seen with a decreasing cropping concentration of SB in the crop rotation and an increasing cropping interval. However, comparing crop rotation fields with equal cropping intervals for SB, there were only slight, insignificant gradations depending on the cropping concentration of SB in the crop rotation.

Table IV-2. Probability values from F-test of fixed effects at the long-term field trial Etzdorf (period 2002-2014, SB - sugar beet)

Parameter	Effect		
	Crop rotation field (CR)	Year	CR*Year
SB root yield	<0.0001	<0.0001	0.1162
White sugar yield	<0.0001	<0.0001	0.1896
White sugar content	0.0039	<0.0001	0.7332
Sugar content	0.0019	<0.0001	0.7541
Standard molasses loss	<0.0001	<0.0001	0.0811
K	<0.0001	<0.0001	0.3982
Na	<0.0001	<0.0001	0.0137
aminoN	0.7480	<0.0001	0.7725

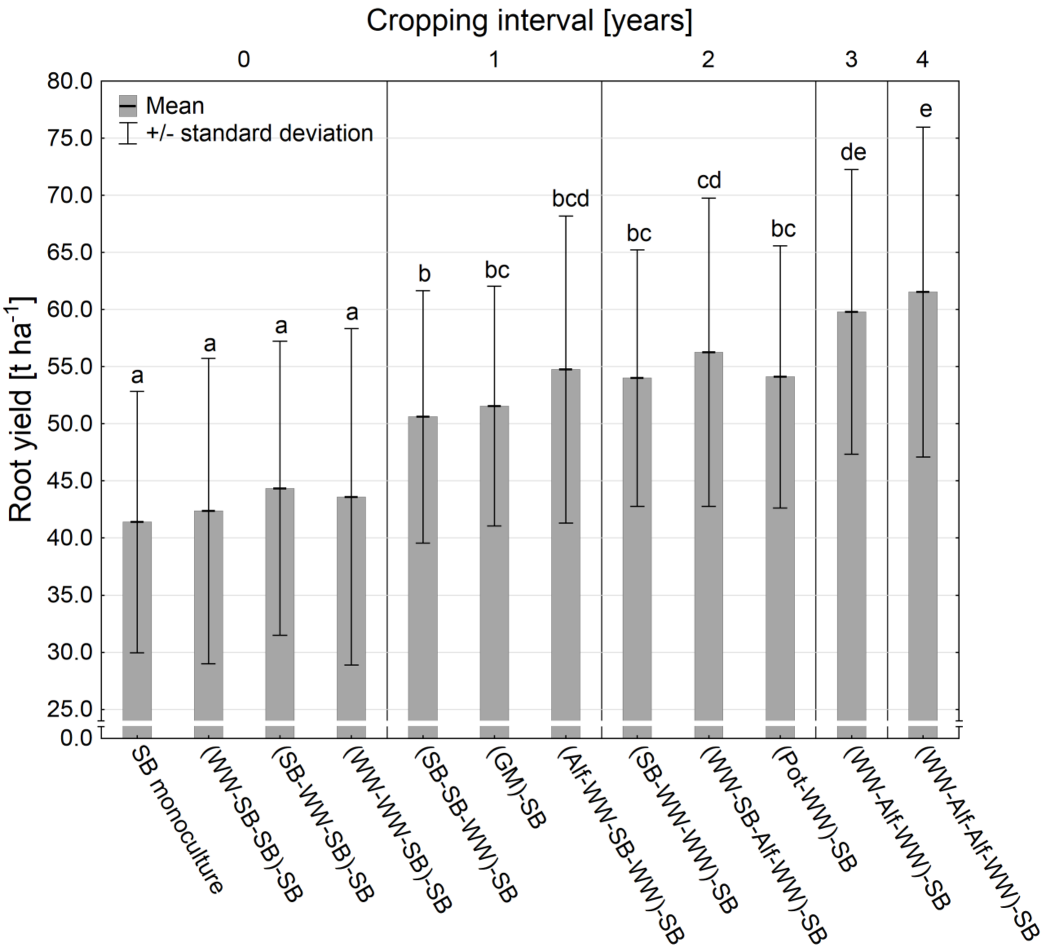

Figure IV-2. Root yield of sugar beet (SB) depending on the crop rotation field at the long-term field trial Etzdorf considered for the period 2002-2014. Different lower case letters indicate significant differences for $p \leq 0.05$ (WW - winter wheat, Alf - alfalfa, GM - grain maize, Pot - potato).

3.1.2 Technological quality

Except the aminoN content, all parameters were influenced significantly by both crop rotation field and year (Table IV-2). SB monoculture showed significantly lower sugar content for the average of all years, and the sugar content of the crop rotation field (WW-SB-SB)-SB was substantially lower, as well (Figure IV-3).

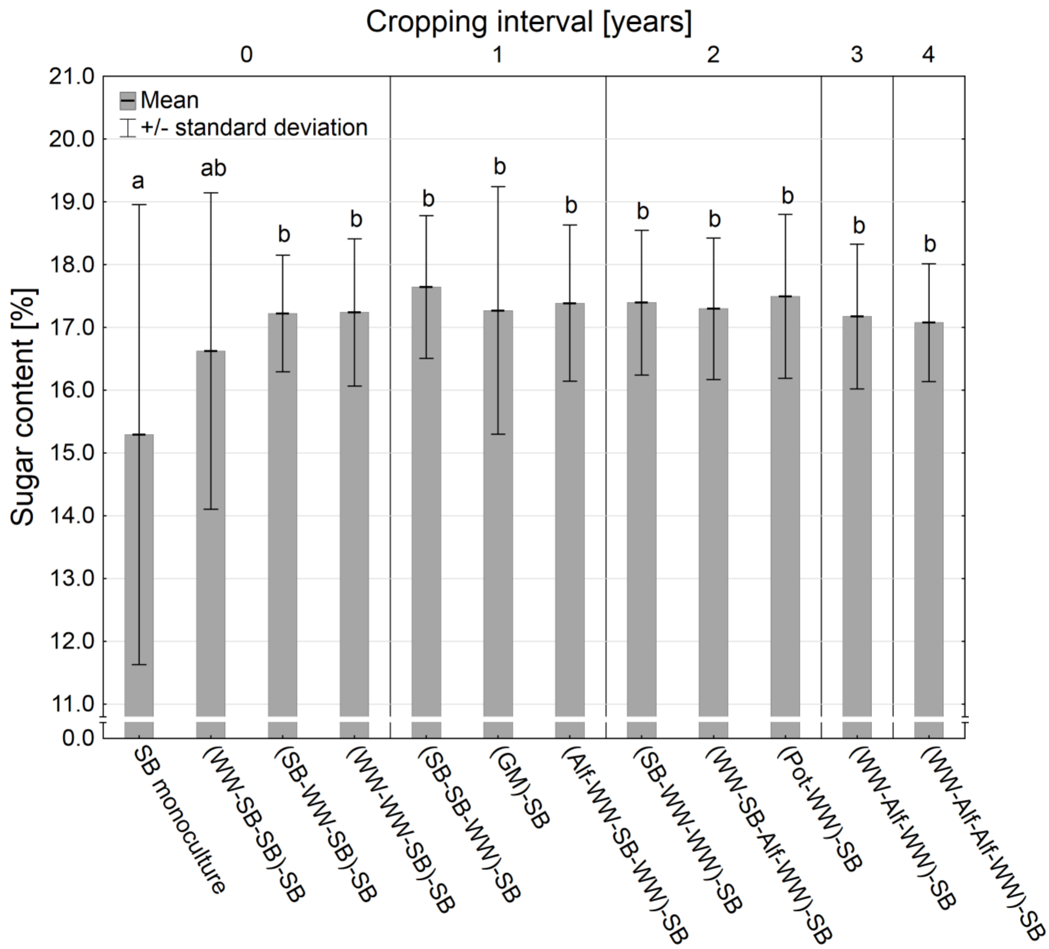

Figure IV-3. Sugar content depending on the crop rotation field at the long-term field trial Etzdorf considered for the period 2002-2014. Different lower case letters indicate significant differences for $p \leq 0.05$ (SB - sugar beet, WW - winter wheat, Alf - alfalfa, GM - grain maize, Pot - potato).

The potassium content was significantly lower for the crop rotation field (GM)-SB and (Pot-WW)-SB compared to (WW-WW-SB)-SB and (WW-Alf-WW)-SB (Table IV-3). All other crop rotation fields could be classified somewhere in between, although there was no relationship in terms of potassium content and SB cropping interval or cropping concentration in the crop rotation. Considering the average for all years, the highest sodium contents were observed in the crop rotation variants with Alf. The lowest sodium contents were seen in the crop rotation fields SB monoculture, (WW-SB-SB)-SB and (SB-SB-WW)-SB. However, due to a significant crop rotation field*year interaction this trend could not be statistically verified. The standard molasses loss was significantly higher for crop rotations including Alf, and significantly lower for the crop rotation fields (GM)-SB and SB monoculture. The lowest white sugar content was observed for SB monoculture. It was not possible to statistically verify the differences compared to all crop rotation fields.

Table IV-3. Potassium content (K), sodium content (Na), amino nitrogen content (aminoN), standard molasses loss (SML) and white sugar content (WSC) for the crop rotation fields at the long-term field trial Etzdorf considered for the period 2002-2014. Different lower case letters indicate significant differences for $p \leq 0.05$ (SB - sugar beet, WW - winter wheat, Alf - alfalfa, GM - grain maize, Pot - potato; CI - cropping interval).

Crop rotation field	CI	K [mmol (100g)$^{-1}$ beet]		Na§	aminoN		SML [%]		WSC [%]	
SB monoculture	0	4.44	*bc*	1.15	2.06	a	2.24	*a*	13.09	*a*
(WW-SB-SB)-SB	0	4.27	*abc*	1.23	2.12	a	2.25	*ab*	14.37	*ab*
(SB-WW-SB)-SB	0	4.35	*bc*	1.26	2.07	a	2.25	*ab*	14.97	*b*
(WW-WW-SB)-SB	0	4.52	*c*	1.86	1.93	a	2.31	*ab*	14.93	*b*
(SB-SB-WW)-SB	1	4.28	*bc*	1.23	2.18	a	2.26	*ab*	15.38	*b*
(GM)-SB	1	3.98	*a*	1.42	2.09	a	2.23	*a*	15.04	*b*
(Alf-WW-SB-WW)-SB	1	4.32	*bc*	2.25	2.09	a	2.37	*bcd*	15.02	*b*
(SB-WW-WW)-SB	2	4.40	*bc*	2.00	2.01	a	2.33	*abc*	15.06	*b*
(WW-SB-Alf-WW)-SB	2	4.30	*bc*	2.58	2.27	a	2.45	*cde*	14.84	*b*
(Pot-WW)-SB	2	4.18	*ab*	2.03	2.09	a	2.33	*ab*	15.17	*b*
(WW-Alf-WW)-SB	3	4.51	*c*	3.05	2.16	a	2.50	*e*	14.67	*ab*
(WW-Alf-Alf-WW)-SB	4	4.32	*bc*	3.00	2.10	a	2.46	*de*	14.61	*ab*

§ no statistical comparison across all years because of significant crop rotation* year interaction

3.1.3 White sugar yield

Similarly to SB root yield, the white sugar yield of the crop rotation fields rose with increasing cropping interval (Figure IV-4). Also, the largest yield growth was present between the variants with cropping intervals of 0 and 1 year. The crop rotation fields with cropping intervals of 3 and 4 years also showed the highest white sugar yield. Even if this could not be statistically verified compared to the crop rotation fields with a cropping interval of 2 years and the crop rotation field (WW-Alf-SB-WW)-SB, the difference was 0.45 t ha^{-1} to 0.68 t ha^{-1} for (WW-Alf-WW)-SB and 0.64 t ha^{-1} to 0.87 t ha^{-1} for (WW-Alf-Alf-WW)-SB.

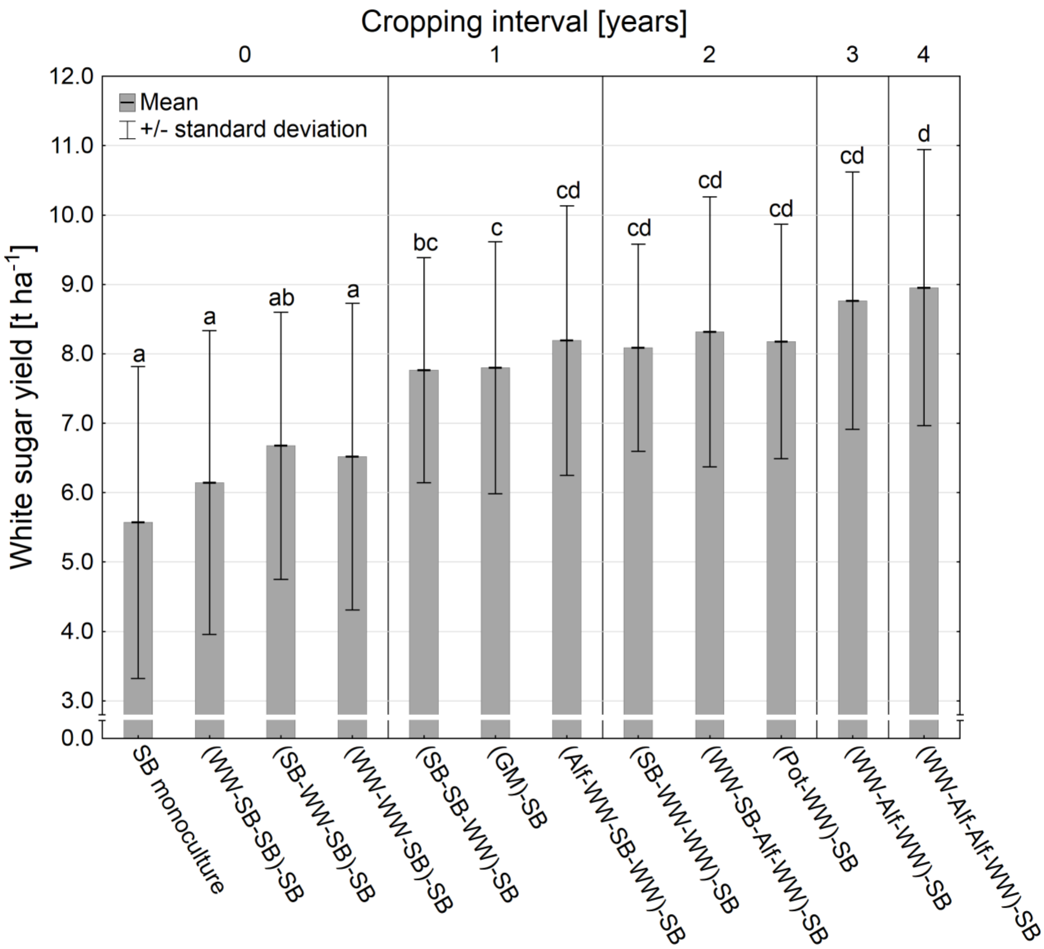

Figure IV-4. White sugar yield depending on the crop rotation field at the long-term field trial Etzdorf considered for the period 2002-2014. Different lower case letters indicate significant differences for $p \leq 0.05$ (SB - sugar beet, WW - winter wheat, Alf - alfalfa, GM - grain maize, Pot - potato).

3.2 Yield stability

There was a close link between the white sugar yield and the yield stability parameter coefficient of variation (Figure IV-5). Coefficient of variation increased with decreasing white sugar yield, indicating a decrease in yield stability. Thus, yield stability decreased with increasing cropping concentration and decreasing cropping interval for SB. A similar link was observed for the parameter ecovalence, where the SB monoculture caused the highest ecovalence and the lowest white sugar yield (Figure IV-5).

The parameters of the regression equations are shown in Table IV-4. The regression line of a crop rotation field with b = 1 and intercept = 0 represents average yield behaviour for the field test presented here. An average behaviour was not shown by the crop rotation fields (WW-WW-SB)-SB and (SB-WW-WW)-SB. The crop rotation field (WW-

WW-SB)-SB caused a significantly lower intercept than 0, whereas the crop rotation field (SB-WW-WW)-SB caused a significantly higher intercept than 0. The slope b of the regression lines was not significantly different from 1 for all crop rotations. However, crop rotation field (SB-WW-WW)-SB tended to a slope b < 1, and the crop rotation field (WW-WW-SB)-SB caused the highest slope b for all crop rotation fields observed. Thus, both SB crop rotation fields ((SB-WW-WW)-SB and (WW-WW-SB)-SB) of the same crop rotation (crop rotation 2, Table IV-1) showed opposite responses to improved environmental conditions. The crop rotation field (SB-WW-WW)-SB responded to improved environmental conditions with below-average white sugar yield growth, and displayed an above-average white sugar yield under unfavourable conditions. The crop rotation field (WW-WW-SB)-SB responded to improved environmental conditions with above-average white sugar yield growth, but it did also demonstrate a below-average white sugar yield under unfavourable conditions.

Deviation from the regression line – shown as root mean square error (RMSE) and its coefficient of variation – was higher for (WW-WW-SB)-SB than for (SB-WW-WW)-SB. By contrast, both crop rotation fields of crop rotation 6 (Table IV-1; (Alf-WW-SB-WW)-SB, (WW-SB-Alf-WW)-SB) showed similar slopes of the regression line and also similar deviations from the regression line, which were low as well. The SB monoculture was characterised by the lowest slope of the regression line and the highest deviation from the regression line. The lowest deviation from the regression line was shown by the crop rotation field (Pot-WW)-SB.

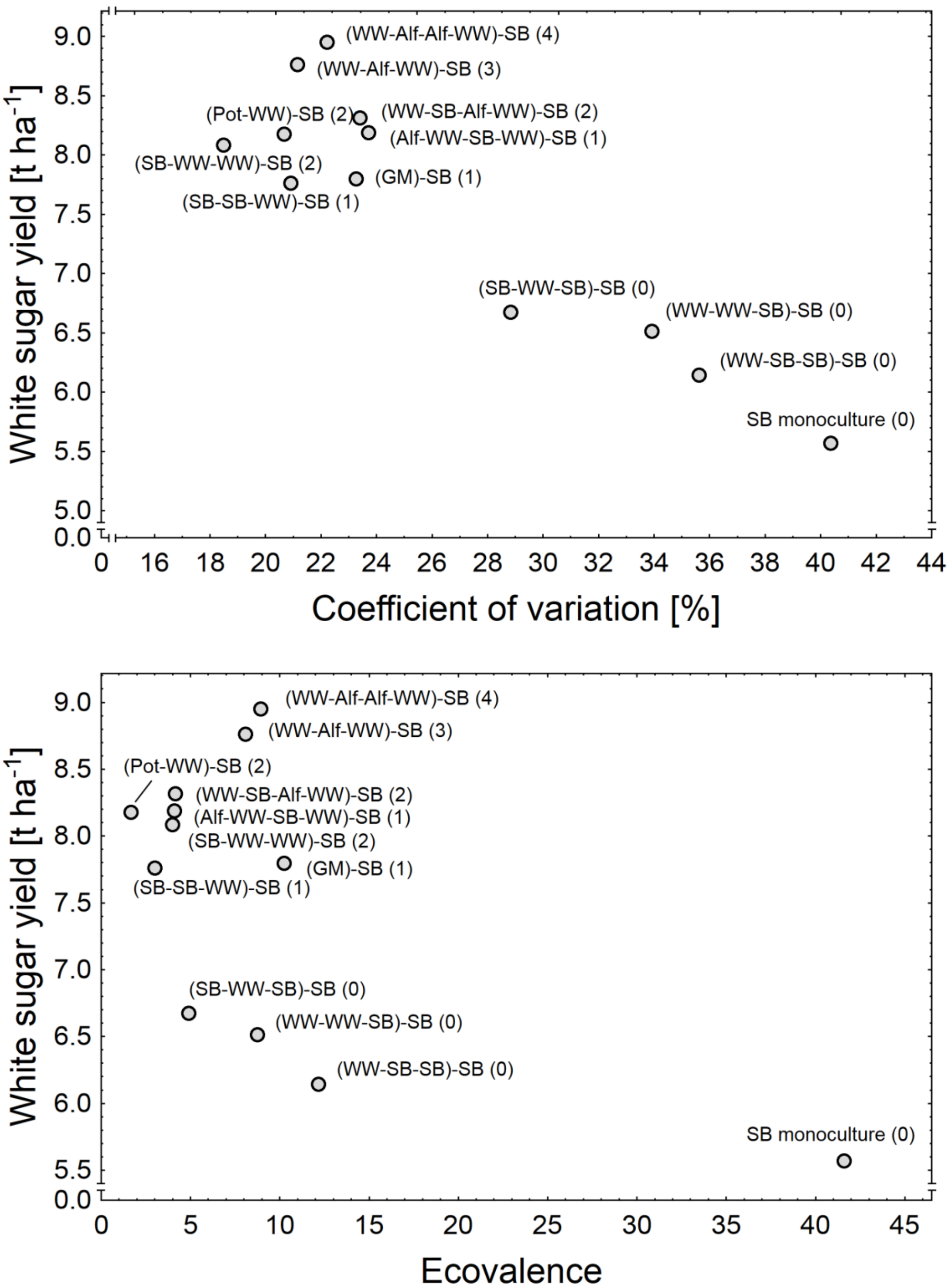

Figure IV-5. Relationship between the yield stability parameters coefficient of variation and ecovalence and white sugar yield across the crop rotation fields (cropping interval in brackets) at the long-term field trial Etzdorf considered for the period 2002-2014 (SB - sugar beet, WW - winter wheat, Alf - alfalfa, GM - grain maize, Pot - potato).

Table IV-4. Values of linear regression analysis for white sugar yield of single crop rotation fields for the environmental mean (annual mean of all crop rotation fields) at the long-term field trial Etzdorf considered for the period 2002-2014 (SB - sugar beet, WW - winter wheat, Alf - alfalfa, GM - grain maize, Pot - potato; CI - cropping interval, CV - coefficient of variation, RMSE - root mean square error).

Crop rotation field	CI	Intercept (ic)	ic = 0 Pr > t	Slope (b)	b = 0 Pr > t
SB monoculture	0	-0.275	0.914	0.772	0.035
(WW-SB-SB)-SB	0	-2.540	0.083	1.146	<0.0001
(SB-WW-SB)-SB	0	-1.385	0.136	1.063	<0.0001
(WW-WW-SB)-SB	0	-2.655	0.029	1.210	<0.0001
(SB-SB-WW)-SB	1	0.884	0.200	0.908	<0.0001
(GM)-SB	1	0.849	0.510	0.917	<0.0001
(Alf-WW-SB-WW)-SB	1	-0.042	0.958	1.086	<0.0001
(SB-WW-WW)-SB	2	1.831	0.020	0.825	<0.0001
(WW-SB-Alf-WW)-SB	2	0.066	0.933	1.088	<0.0001
(Pot-WW)-SB	2	0.867	0.112	0.964	<0.0001
(WW-Alf-WW)-SB	3	1.395	0.239	0.972	<0.0001
(WW-Alf-Alf-WW)-SB	4	1.005	0.410	1.049	<0.0001

Table IV-4. Continuation.

Crop rotation field	CI	b = 1 Pr > F	R^2	RMSE	CV (RMSE)
SB monoculture	0	0.491	0.34	1.90	34.1
(WW-SB-SB)-SB	0	0.414	0.80	1.02	16.6
(SB-WW-SB)-SB	0	0.580	0.89	0.66	9.8
(WW-WW-SB)-SB	0	0.153	0.88	0.81	12.4
(SB-SB-WW)-SB	1	0.293	0.91	0.50	6.4
(GM)-SB	1	0.616	0.75	0.95	12.2
(Alf-WW-SB-WW)-SB	1	0.407	0.92	0.59	7.2
(SB-WW-WW)-SB	2	0.069	0.89	0.51	6.4
(WW-SB-Alf-WW)-SB	2	0.395	0.92	0.59	7.1
(Pot-WW)-SB	2	0.594	0.95	0.38	4.7
(WW-Alf-WW)-SB	3	0.852	0.81	0.85	9.7
(WW-Alf-Alf-WW)-SB	4	0.754	0.81	0.90	10.0

4 Discussion

The article presents results on the influence of varying SB crop rotations on yield, technological quality and yield stability at the end of the long-term field trial Etzdorf after 45 trial years. Therefore, results are discussed with special regard to former investigations at this field trial.

4.1 Yield and technological quality of sugar beet

The differences presented in SB root yield and white sugar yield are in keeping with previous investigations at the Etzdorf site (Liste et al., 1992; Deumelandt et al., 2010) As the cropping concentration of SB in the crop rotation decreases or the cropping interval increases, the root yield and white sugar yield increase. The greatest yield increase was observed between the SB crop rotation fields with SB as a preceding crop and those with a cropping interval of one year. In the older literature, evidence of similar relationships for SB was also detected at other experimental sites (Gonet and Gonet, 1976; Smukalski and Rogasik, 1977; Fichtner and Berger, 1985; Wicke and Matthies, 1990). However, there are only few more recent results available in this context (Hlisnikovsky et al., 2014). Increasing the cropping concentration of SB in the crop rotation does not however always result in such yield depressions. Draycott et al. (1978) found no yield differences as a function of SB concentration after 12 years of investigation. It took 10 years before Kachel et al. (1981) were able to detect lower yield in SB monoculture. Infestation with the beet cyst nematode *Heterodera schachtii* Schmidt has a decisive impact on the yield depression described in the literature and the results presented here. Alongside soil-borne diseases such as black root (*Aphanomyces cochlioides* Drechsler, Schäufele and Winner, 1989), seedling damping off caused by *Rhizoctonia solani* (Windels and Nabben, 1989) and *Pythium* root rot (Harveson et al., 2009) this pest is one of the main reasons for the marked yield loss of SB cultivated in narrow crop rotation and monoculture (Fichtner et al., 1984b; Fichtner and Berger, 1985; Liste et al., 1992; Deumelandt et al., 2010). The Etzdorf long-term field trial was already infested with *H. schachtii* when the trial was set up in 1970 (Fischer and Liste, 1979). Therefore an identical trial was set up in parallel in Andisleben (near Erfurt, Thuringia, Germany), at a site of similar soil typology and climatic conditions which was not infested with *H. schachtii*. At the Etzdorf site, considerable yield differences as a function of the cropping concentration and cropping interval of SB were detected compared to Andisleben just a few years the trial was carried out (Fischer and Liste, 1979). By contrast, even after 20 years there were far less considerable yield differences at the Andisleben site (Liste et al., 1990). The population, abundance and adverse effects of *H. schachtii* as a function of the crop rotation system was already evaluated in detail at the long-term field trial in Etzdorf (Fischer et al., 1981a; Liste et al., 1992; Deumelandt et al., 2010) which is why no further investigations of the nematode population were conducted here. These authors established a clear link between the cropping interval for SB, the *H.*

schachtii population and the root yield, whereby the *H. schachtii* population decreases and the root yield rises as the cropping interval increases. Fichtner et al. (1984b) and Wicke and Matthies (1990) observed similar links at other sites.

Since about 2010, it is a common agricultural practise to cultivate nematode-tolerant SB varieties when the soil is infested with *H. schachtii*. Hereby, the yield decrease due to nematode infestation is reduced compared to the cultivation of susceptible varieties (Hauer et al., 2015a). However, it was not decided to cultivate a nematode-tolerant variety at the long-term field trial Etzdorf to be consistent over the entire trial duration.

When interpreting the results, in addition to the cropping interval and cropping concentration, it is necessary to consider the impact of the complementary crops WW, Alf, Pot and GM. It was however not possible to conduct a statistical verification of the effects of the preceding or complementary crops, since not all combinations of the cropping interval, cropping concentration and the complementary crops cultivated were present. It is therefore not possible to identify the extent to which the high root yield and white sugar yield of the crop rotation fields (WW-Alf-Alf-WW)-SB and (WW-Alf-WW)-SB were caused by the long cropping intervals or by the integration of Alf. Even so, it can be assumed that cultivating Alf causes an increase in root yield and white sugar yield. Comparing the crop rotation field (Pot-WW)-SB (33 % cropping concentration, cropping interval of 2 years) with the field (Alf-WW-SB-WW)-SB (40 % cropping concentration, cropping interval of 1 year), the crop rotation field with Alf displays a similarly high root yield and white sugar yield despite the fact that the cropping concentration is higher and the cropping interval shorter. The integration of Alf into the crop rotation system is presumably able to offset the yield loss caused by an increased cropping concentration and shorter cropping interval, and to increase yield. The concept of the long term field trial Etzdorf was also focused on soil and crop health by setting up well-balanced SB crop rotations including cereals and forage crops (Duda and Liste, 1991). Therefore, Alf was chosen as a common forage crop. Liste and Fischer (1988) believe that cultivating Alf in the Etzdorf long-term field trial results in increased yields because of its phytosanitary effect and ability to improve the soil structure. The latter should make it easier for SB roots to penetrate deeper soil layers and thus enable them to survive prolonged dry periods. However, it has not yet been possible to confirm such an influence on soil structure (Deumelandt et al., 2010). The higher root yield and white sugar yield in the crop rotations with Alf is presumably largely based on a phytosanitary effect with regard to *H. schachtii*. At the long-term field trial Etzdorf, crop rotations including Alf caused a slightly higher soil organic carbon content (soil depth 0-30 cm) and a more positive soil organic matter balance (Deumelandt et al., 2010). Suppling soil with organic material can enhance microbial diversity in the soil and promotes the parasitization of nematode cysts by fungi (Widmer et al., 2002). This was also shown for the long-term field trial Etzdorf as the highest rate of parasitized cysts and the lowest vitality of the larvae was detected when Alf was included in the crop rotation (Duda and Liste, 1991).

In the present investigations, the sugar content was only affected to the extent that SB monoculture displayed the lowest sugar content. This confirms the results of Rychcik and Zawiślak (2002), which also found lower sugar contents in SB monoculture compared to crop rotation. The high standard molasses loss of the crop rotation fields with Alf in the crop rotation, which were mainly caused by high sodium contents, reduced the white sugar content to the extent that these crop rotation fields did not display a significantly higher white sugar content compared to SB monoculture.

The low standard molasses loss in the crop rotation fields (GM)-SB and SB monoculture were attributable to the low potassium content in (GM)-SB and the low sodium content in SB monoculture. The results for the potassium content could not be attributed to the root yield or the crop rotation position of SB, since the crop rotation fields (WW-WW-SB)-SB and (WW-Alf-WW)-SB for example displayed similarly high potassium contents. In SB, sodium and potassium can be partially replaced as nutrients (Draycott, 1993). If there is a low potassium concentration in the soil solution, sodium is absorbed at a higher rate (Mengel and Forster, 1973). For the high-yielding crop rotation fields (WW-Alf-Alf-WW)-SB, (WW-Alf-WW)-SB, (WW-SB-Alf-WW)-SB and (Alf-WW-SB-WW)-SB, it is likely that the potassium contents in the soil solution were not sufficient to meet the demand, and that the SB of these crop rotation fields absorbed a greater amount of sodium from the soil solution. However, no routine, annual analysis of the soil solution was conducted for these nutrients, meaning these presumptions cannot be proven.

4.2 Yield stability

Methods used to identify the yield stability of different varieties can also be used to compare the yield stability of different cropping systems (Piepho, 1998). The parameters applied, coefficient of variation, ecovalence, and regression analysis are commonly used to assess the yield stability of different crop rotations (Berzsenyi et al., 2000; Christen, 2001; Grover et al., 2009; Coulter et al., 2011; Cociu, 2012; Borrelli et al., 2014). Since the average annual yield across all crop rotation fields and the average yield of all crop rotation fields from the trial period are used to calculate ecovalence and for the linear regression analysis, these methods can only be used to assess the yield stability of a crop rotation field in the context of the other crop rotation fields which were tested.

Crop rotation fields which are characterized by high white sugar yields, low coefficients of variation, low ecovalences and low deviations from the regression line as well as a slope b of the regression line which is close to 1, can be classified as stable (Piepho, 1998). Thus, crop rotation fields with a cropping interval for SB of at least 2 years and the crop rotation field (Alf-WW-SB-WW)-SB displayed higher yield stability than crop rotation fields with a cropping interval of 1 year or when SB was cultivated after SB (cropping interval 0 years). Accordingly, information from the literature for wheat and maize, which demonstrate a higher yield stability of crop rotations compared to monoculture (Cociu, 2012; Borrelli et al., 2014), is also demonstrated for SB by the presented results for the first time. Even if wheat and maize monocultures are common practices in some regions, it is not likely that SB monoculture will become established in practice, due to the marked yield loss and low yield stability.

The lower yield stability of crop rotation fields with cropping intervals of 0 and 1 year is likely due to a higher sensitivity against external conditions, like water and nutrient supply as well as weed and pest occurrence. In this context, Rychcik and Zawiślak (2002) were able to prove that the application of herbicides in combination with fungicides increased white sugar yield of SB monoculture by about 14 %, whereas white sugar yield of SB cultivated in crop rotation only increased by about 4 %. Similarly, SB cultivated in extended crop rotation (cropping interval 7 years) caused higher root yield than SB cultivated in narrow crop rotation (cropping interval 1 year) which is due to a better nutrient utilization and a better resilience against unfavourable weather conditions (Hlisnikovsky et al., 2014). This can probably be attributed to the infestation with *H. schachtii* which decreases the rate of photosynthesis and the nitrogen uptake of SB (Schmitz et al., 2006). Infestation with *H. schachtii* is also discussed to reduce water uptake. However, in case of sufficient water supply and *H. schachtii* occurrence, the evaluations by Hauer et al. (2015a) displayed similar evapotranspiration of varieties which are either susceptible, tolerant or resistant towards *H.schachtii*.

With regard to the linear regression analysis, the slope b provides information about the response of different crop rotation fields to improved environmental conditions, and slopes $b > 1$ indicate a more sensitive response than slopes $b < 1$ (Ober et al., 2004). For the present results, all crop rotation fields with a cropping interval of 0 years, except SB monoculture, showed a high response to environmental conditions. White sugar yield for SB monoculture was only weakly predicted by the linear regression analyses. Thus, the slope b of the regression line does not give valid information about the response to environmental conditions for SB monoculture.

For the crop rotations which consist of several crop rotation fields with SB, it is necessary to consider the yields as well as the yield stabilities of all crop rotation fields in one crop rotation as a whole. The first crop rotation fields of the crop rotations SB-SB-SB-WW and SB-SB-WW-WW achieve root yield and white sugar yield which is not significantly different from those of the other crop rotation fields with a cropping interval of 1 or 2 years. However, yield drop considerably in the second or third crop rotation field with SB. This applies similarly to yield stability. In the crop rotation SB-WW-SB-Alf-WW, both crop rotation fields show high and stable yield, since SB is not cultivated after SB here and Alf is also integrated.

5 Conclusions

The choice of appropriate crop rotation for SB cultivation results from different demands. From an ecological perspective, those crop rotations which achieve the highest SB root yield and white sugar yield from the same input – and thus best exploit the benefits of crop rotation – are advantageous. With this in mind, the results presented from the long-term field trial Etzdorf show that increasing cropping intervals and decreasing cropping concentrations for SB in the crop rotation and integrating Alf lead to the highest root yield and white sugar yield. From an economic perspective, it may also be advantageous to consider crop rotations with lower but stable yield and higher SB cropping concentration as possible. Under the experimental conditions at the Etzdorf site, the crop rotations SB-WW-SB-Alf-WW and SB-Pot-WW fulfil these conditions. Without integrating Alf into the crop rotation, cropping intervals of at least 2 years are necessary in order to ensure high yield stability under the conditions of the long-term field trial Etzdorf. When integrating Alf, the cropping interval may under certain circumstances be reduced to 1 year. With regard to both the level and stability of yield, cultivating SB after SB should be avoided as it makes no ecological or economic sense. Ultimately, however, any ecological as well as economic evaluation should take into account the overall performance of all the crops grown in a crop rotation system.

V Epilogue

The effects of specialised sugar beet crop rotations on soil fertility and on sugar beet yield and yield stability are discussed below (sections 1 and 2 respectively). The corresponding hypotheses are first examined before looking at the potentials and limits of specialised sugar beet crop rotations in the context of the relevant topic.

1 Effects of specialised sugar beet crop rotations on soil fertility

1.1 Soil organic matter content

1.1.1 Discussion of hypothesis

Hypothesis 1: *Under changing cultivation conditions, the soil organic matter content is reduced by increasing the sugar beet cropping concentration. The change in soil organic matter can be mapped to a sufficiently accurate degree using humus balances.*

In order to respond to this hypothesis using the present results, it is important to bear in mind the following points: First of all, the results described in chapter II from the long-term field trial in Etzdorf cannot be clearly attributed to the context of changing sugar beet cultivation conditions. On the one hand, nowadays the removal of beet leaves and mechanical weed control are very rare (Märländer et al., 2003), and ploughing in autumn is not any longer the dominant tillage method for sugar beet in Germany (Buhre et al., 2014). On the other hand, the manner in which the trial was conducted in recent years no longer corresponds to the standard for sugar beet cultivation from the 1970s; technical progress is also unavoidable in long-term trials. For example, intensive seedbed preparation and mechanical weed control, which were both practised as standard at the beginning of the trial, have been significantly reduced thanks to the use of effective herbicides. In addition, the yield increase seen in practice as a result of breeding improvements and climate changes (Scott and Jaggard, 2000) is also reflected in the Etzdorf trial (Kuntzsch, 2001), which is associated with an increased carbon input (Franko, 1997; Wiesmeier et al., 2014).

A second point of criticism concerns the design of the trial, which involves two real field replications and two repeated measures per plot. Differences in the soil organic carbon (=TOC) stock of 2.9 and 3.0 t ha^{-1} are not statistically significant. It may is possible to support these differences statistically by increasing the extent of sampling. Indeed Knebl et al. (2015) calculated the minimum detectable differences for the soil organic carbon stock in a field trial, taking various possibilities for detecting outliers into account. In the trial with four real field replications and six repeated measures, it was possible to significantly reduce the variability of the sample by eliminating outliers at plot level. In this way the minimum detectable differences dropped by a factor of 0.53 and were approximately 1.77 t ha^{-1} (Knebl et al., 2015).

Considering the limitations mentioned, the hypothesis is assumed to be true. The soil organic matter content can decline as the sugar beet cropping concentration increases. Due to changing cultivation conditions, however, this reduction is smaller at the trial site than described in the literature. While humus balances can map this trend, they do not permit any conclusions about actual differences in the soil organic carbon stock.

In the long-term field trial at Etzdorf, the focus was on investigating the impact of the crop rotation on sugar beet yield parameters and the characterisation of crop rotation related pathogens. When the field trial was set up in 1970, the relationship between the crop rotation variant and soil organic carbon content was of secondary interest, and this parameter was only determined at irregular intervals. Table V-1 summarises the results of these studies, which are available from the literature, as well as own results.

Table V-1. Soil organic carbon content [g kg^{-1}] of crop rotations at the long-term field trial Etzdorf based on literature data and own results (SB - sugar beet, WW - winter wheat, Alf - alfalfa, Pot - potato, GM - grain maize).

		Crop rotation							
Year	Soil depth [cm]	SB-WW-Alf-WW	SB-SB-WW-WW	SB-Pot-WW	SB-WW-Alf-Alf-WW	SB-SB-SB-WW	SB-Alf-WW-AB-WW	SB-GM	SB monoculture
1970[1]	0-20	21.7 (20.6 to 23.1)							
1971/1975[2]	0-20	21.4	--	--	--	--	--	--	21.6
1986/1987[3]	0-100	16.6	17.0	17.9	16.5	16.8	17.5	--	16.5
2006[4]	0-30	22.4	21.3	21.8	22.4	21.3	--	--	20.8
2010/2012[5]	0-30	--	22.6	--	--	22.2	--	21.7	21.9
2010/2012[5]	30-45	--	17.3	--	--	18.4	--	18.3	18.4

[1] Fischer (1977), initial analysis, 106 homogenously distributed samples, method unknown

[2] Fischer and Beleites (1979), method unknown

[3] Krieger (1989), only plots of the second field replication, dry combustion method (TGL 25418/4)

[4] Deumelandt et al. (2010), dry combustion method (ISO 10694:1995-03-01)

[5] own results, Götze et al. (2016b), dry combustion method (ISO 10694:1995-03-01)

These data can only provide a limited insight into general as well as crop rotation-specific changes to soil organic carbon content during the trial period, because the methods used are not uniform and are not known in some cases. Furthermore, the different sampling depths make it more difficult to classify the data. The only variant considered in all investigations was SB monoculture, and there is no clear evidence of a significant decrease in soil organic carbon content. This can probably be attributed to the routine addition of manure.

1.1.2 Preservation of soil organic matter content in specialised sugar beet crop rotations

The cropping concentration of sugar beet can only be increased to the extent that there is a sufficient supply of organic matter to preserve the soil organic matter content throughout the whole crop rotation. The amount of organic matter needed depends on carbon losses due to decomposition as well as the supply of organic carbon through biomass and organic fertilizer (Janzen et al., 1997). The largest carbon loss is generally observed when the ground is used as fallow land, whereas soil organic carbon content increases if biomass production increases as a result of cultivating annual or even perennial crops as well as grassland (Blair et al., 2006). Compared to cereals, when cultivating sugar beets smaller amounts of carbon remain in the soil, even in the case of increased dry matter yield of sugar beets, since more than 85 % of the biomass carbon which has formed is exported through harvesting (sugar beet root) (Wiesmeier et al., 2014). In addition, the cultivation of sugar beet as a summer annual crop is characterised by a comparatively long fallow period after the preceding crop has been harvested. The cultivation of catch crops for green manuring before sowing sugar beets permits perennial vegetation and can potentially supply the soil with organic matter. In a meta-analysis of 37 international studies, Poeplau and Don (2015) calculated a significant increase in the soil organic carbon stock (0-22 cm) of 0.32 t ha^{-1} a^{-1} for the cultivation of winter catch crops. However, these data cannot simply be extrapolated to the cultivation of mustard or radish, which in Central Europe are two typical summer catch crops (Buhre et al., 2014) before sugar beet. Where these catch crops were cultivated annually, after 13 and 17 years Constantin et al. (2010) found evidence of an increase in the soil organic carbon stock (0-30 cm) of approximately 1.0 t ha^{-1}, although this was not significant (average dry matter production including roots; mustard: 1.2 t ha^{-1} a^{-1}, radish: 1.6 t ha^{-1} a^{-1}). This corresponds to an annual contribution to the soil organic carbon stock (0-30 cm) of between 0.06 and 0.08 t ha^{-1} and is considerably lower than for winter catch crops (Poeplau and Don, 2015) and for the values calculated by Mutegi et al. (2013) for radish (0.16 t $ha^{-1}a^{-1}$) and the humus balancing values (0.14 to 0.18 t ha^{-1} a^{-1} plus humus supply from above-ground biomass; calculated according to VDLUFA, 2004). The biomass production of catch crops depends on the available vegetation time and is subject to considerable annual fluctuations. For example, after three years of investigation Talgre et al. (2011) observed considerable variation in the dry matter production of mustard and radish depending on the time of sowing and subsequent weather patterns in the late summer and autumn. In this investigation, dry matter production (including above-ground biomass and roots, 0-30 cm soil depth) varied between 0.6 and 3.0 t ha^{-1} for mustard, and 0.6 and 3.5 t ha^{-1} for radish. The overall impact on soil organic matter content of cultivating catch crops before sugar beet can be regarded as low.

In sugar beet crop rotations, it is therefore necessary to integrate crops with a significantly positive impact on the soil organic matter content. In particular, cultivating forage crops or legumes for several years leads to an increase in soil organic matter content (Campbell et al., 1991; Angers, 1992; Persson et al., 2008); however, these crops are not currently grown to a significant extent in crop rotations with sugar beet (Buhre et al., 2014). In practice-relevant sugar beet crop rotations, the cultivation of winter wheat can contribute to an adequate supply of organic matter, since this crop leaves behind a large amount of carbon, particularly if the straw remains on the field (Wiesmeier et al., 2014). Even when the straw was removed in winter wheat monoculture, Triberti et al. (2016) calculated a higher soil organic carbon stock (0-40 cm) than in an SB-WW crop rotation. In the present investigations integrating winter wheat into the crop rotation also resulted in a slight increase in the soil organic carbon stock (0-30 cm). Table V-2 gives an overview of the present as well as published humus balances for crop rotations with varying proportions of sugar beet and winter wheat. An even humus balance (-75 to 100 kg humus-C ha^{-1} a^{-1}, according to VDLUFA, 2014) was only calculated by Jacobs et al. (2016a) for cultivating winter wheat twice, straw manure and integration of the catch crop mustard for green manuring. In all of the studies, substituting a winter wheat crop rotation field with silage maize or sugar beet resulted in more negative humus balances, regardless of whether by-products were removed (Deumelandt et al., 2010; Götze et al., 2016b) or remained on the field (Jacobs et al., 2016a). This means that increasing the sugar beet cropping concentration would even result in significantly more negative humus balances if the by-products were left on the field and with additional green manuring through catch cropping.

Table V-2. Calculated humus balances [kg humus-C $ha^{-1}a^{-1}$] of different sugar beet crop rotations (SB - sugar beet, WW - winter wheat, SM - silage maize, Mu - catch crop mustard).

	Crop rotation						
Reference	SB-WW-WW	Mu_SB-WW-WW	SB-WW-SM	SB-WW-Mu_SM	SB-SB-WW-WW	SB-SB-SB-WW	SB monoculture
Deumelandt and Christen (2008)[1]	-140	--	-447	--	--	--	--
Deumelandt et al. (2010)[2]	--	--	--	--	-120	-240	-360
Jacobs et al. (2016a)[3]	--	-32	--	-394	--	--	-736
own results (Götze et al., 2016b)[4]	--	--	--	--	-308	-394	-509

[1] farm data, Germany, HU method according to Hülsbergen (2003)

[2] long term field trial Etzdorf, Germany, period 1992-2006, 10 t $ha^{-1}a^{-1}$ farmyard manure, according to VDLUFA (2004)

[3] field trial data, Germany, return of by-products and catch crop Mu, HU method according to Hülsbergen (2003)

[4] long-term field trial Etzdorf, Germany, peridod 1998-2011, 8.6 t ha^{-1} a^{-1} farmyard manure, HU method according to Hülsbergen (2003)

The method applied for humus balancing in this study as well as other methods (e.g. VDLUFA, 2004) do not distinguish between conventional tillage and reduced tillage. According to Fageria (2012), the C/N ratios of the harvest residues after conventional tillage have a greater impact on soil organic matter decomposition than in no-tillage conditions, and harvest residues with a close C/N ratio favour soil organic matter decomposition. Sugar beet leaves are characterised by a far closer C/N ratio and higher N mineralisation than wheat straw (Bending et al., 2002). Higher mineralisation of sugar beet leaves could therefore be expected in the case of conventional tillage. Nevertheless, Hoffmann et al. (1997) observed a higher N mineralisation rate of sugar beet leaves with conservation tillage, which resulted from increased microbial biomass in the cultivation horizon (0-10 cm).

If, in the case of specialised sugar beet crop rotations, the demand for organic matter cannot be covered in the crop rotation itself, then organic fertilizers should be applied.

In order to offset the humus demand of sugar beet (see above) calculated in Jacobs et al. (2016a), it is necessary to apply approximately 4.4 t ha^{-1} of dry matter farmyard manure per sugar beet cultivation year (calculated according to VDLUFA, 2014).

1.2 Soil structure and soil compaction risk

1.2.1 Discussion of hypothesis

Hypothesis 2: *Integrating sugar beet in crop rotations increases the risk of soil compaction in the whole crop rotation due to the operation-specific technology used and high water contents at harvest.*

The hypothesis is confirmed on the basis of the current results (chapter III), with the highest soil compaction risks calculated for crop rotations with sugar beet. This applied to both the lower topsoil (20 cm soil depth) and the subsoil (35 cm soil depth). If deep loosening of the topsoil is not planned, then it is important to avoid soil compaction in the lower topsoil, while soil compaction in the subsoil should always be avoided. However, the calculations only apply to the conditions assumed for reduced tillage during modelling. Soil compaction risks may differ for conventional tillage, since the soil strength in the topsoil is usually lower (Zink et al., 2010) and driving on the plough pan during primary tillage also needs to be taken into account.

The higher soil compaction risks when cultivating sugar beet are caused primarily by the operation-specific machinery used, and not by higher soil water contents at harvest. On average for the reference period, lower soil water content is calculated for sugar beet harvest than for winter wheat and silage maize harvest, and even the highest soil water content modelled for sugar beet harvest is below the highest values for silage maize and winter wheat harvest. This is also the case if the sugar beet harvest occurs at a later date, because similar average soil water content for sugar beet harvest to those observed for winter wheat and silage maize harvest at the Aiterhofen site is not achieved until 2 and 30 November respectively. However, it is important to note that the modelling in REPRO uses the soil water content for the depth of 0-60 cm and does not consider any differences depending on depth. The soil water contents calculated for this depth do not therefore apply without restriction to the real conditions in the field. The reason for the lower soil water content when cultivating sugar beet is the vegetation period. Sugar beets display positive growth rates until harvest in November, with the highest growth rates from early July until early September (Stockfisch et al., 2002; Kenter et al., 2006).

Accordingly, transpiration also continues until harvest, and at the time of harvest soil water content is lower for sugar beet compared to silage maize and winter wheat.

It should also be remembered that influences on soil water content caused by the cultivation of mustard as a catch crop were not taken into account. These data could in principle be integrated into the module, although this would require considerable effort. However, it should be possible for agricultural consultants and practitioners to model the soil compaction risk using a manageable amount of input data (Rücknagel, 2007). In this regard, the use of soil water content data for the specific main crops represents the best compromise between accuracy, data availability and practicability. In the present investigations, the inaccuracies are negligible. Taking into account the water consumption of catch crops could influence the soil water content in the spring in particular. This could potentially result in differing soil compaction risks for the seedbed preparation and sowing activities for sugar beets and silage maize as well as for the application of plant protection products and fertilizers in the spring. However, the low wheel loads and high working widths associated with these operations mean they only have a minor influence on soil compaction risks in the entire crop rotation. Furthermore, investigations by the German Meteorological Service (DWD) have shown that even when catch crops are grown in the prevailing, low-precipitation conditions of Central Germany, there are similar soil water contents in the spring to when no catch crops are grown (Böttcher et al., 2014).

The higher soil compaction risks in crop rotations inclduing sugar beet are primarily due to the specific harvesting method. Compared to the machinery used to harvest silage maize and winter wheat, the equipment assumed for harvesting sugar beets has significantly higher axle loads and a smaller working width and, therefore, involves a higher proportion of wheeled area. The calculation of the soil compaction risk does not take into account current developments of agricultural engineering in terms of soil preserving sugar beet harvesting techniques. These developments are however discussed in the following. Nevertheless, the scenario with half-full hoppers and adjusted tyre inflation pressure in years with high soil water contents is considered as one option for avoiding soil compaction risks when harvesting sugar beets, and the results confirm a reduction in the soil compaction risk when this method is applied.

1.2.2 Avoiding soil compaction in specialised sugar beet crop rotations

When specialising crop rotations by increasing the sugar beet cropping concentration, sugar beet acreage increases, and consequently so does the soil compaction risk of the overall crop rotation. For example, for a model farm Götze et al. (2015) calculated higher soil compaction risks in the lower topsoil (20 cm soil depth) for sugar beet monoculture than for the crop rotations Mu_SB-WW-WW and SB-WW-Mu_SM.

In order to ensure the functionality of the soil structure in specialised sugar beet crop rotations, soil compaction must be avoided when harvesting sugar beets. One suitable approach which is discussed in this regard is using reduced tillage, since this tillage method increases the soil strength in the topsoil (Brunotte et al., 2013). As a result, the applied mechanical stress is compensated more horizontally, which reduces the stress propagation at greater soil depths (Zink et al., 2010). This relationship is also taken into account when calculating the soil compaction risk for reduced tillage in REPRO (Rücknagel et al., 2015), and therefore forms part of the basis of the present results. However, if soil water content is high, then even reduced tillage can result in soil compaction in the subsoil (soil depth 40-45 cm) when the ground is driven over with standard six-row sugar beet harvesters (Koch et al., 2008). The results of Koch et al. (2008) are confirmed by the present results, because medium soil compaction risks for the subsoil (soil depth 35 cm) are calculated for sugar beet and winter wheat harvest in individual years, and thus a deterioration of the soil structure is probable. The use of conservation tillage methods can therefore only contribute to preventing soil compaction when combined with other measures. The stabilisation of the soil structure and increasing the soil strength through catch cropping have been discussed in this context (Brunotte et al., 2013). However, Rücknagel et al. (2016) did not find higher mechanical stability of the soil structure (9-12 cm) after cultivating large-grain legumes as catch crops. The reason given for this is poor root penetration resulting from catch crops’ brief vegetation period, and also insufficient support for biological activity.

The use of technological possibilities to reduce mechanical soil stress and the optimisation of cultivation practices are the most effective approaches for avoiding soil compaction. When the soil water content remains constant, the axle load, frequency of wheeling and tyre inflation pressure have the greatest impact on the degree of soil compaction (Canillas and Salokhe, 2001). The method applied in this study, which involves restricting the hopper load to 50 % for harvesting during years with a medium or high soil compaction risk and adjusting the tyre inflation pressure to the technically permissible minimum, reduces the mechanical soil stress when harvesting sugar beets by reducing the axle load by 5.39 t and lowering the tyre inflation pressure from 270 kPa to 200 kPa. However, a sugar beet harvester with a large 20 t hopper has also a high tare weight (approximately 25 t), and even with a 50 % hopper load it is heavier (weight approximately 35 t) than a smaller harvester with a full hopper (total weight approximatly 25 t, Brantner et al., 2014). Using a smaller harvester with large, soil preserving tyres could therefore contribute to further reducing the of soil compaction risk. In practice, however, this approach and using modern nine or twelve row harvesters may result in a higher frequency of wheeling. By halving the hopper capacity or doubling the working width, the potential distance travelled to fill the hopper is halved. If the actual length of the field exceeds the potential distance, then it is necessary to offload the beets onto transport vehicles, which increases the frequency of wheeling. Even with lower wheel loads, an impairment of the soil structure can be expected with repeated wheeling. In the case of a single wheeling with a wheel load of 12 t and large tyres, Schjønning et al. (2016) measured lower penetration resistance at 0-50 cm soil depth than for a wheel load of 7 t and five passes. In both variants, tyre inflation pressure was between 150 kPa and 300 kPa.

Driving over the soil repeatedly with high axle loads when water content is high should therefore always be avoided. Table V-3 lists the soil compaction indices calculated for the sugar beet harvest at the Aiterhofen model farm in the individual years along with the corresponding soil water contents. The soil compaction indices for the Etzdorf site are also calculated for reduce tillage conditions. Both sites display varying precompression stress values and sugar beets were harvested between 12 and 15 October. If a deep loosening of the topsoil is to be avoided, then the maximum hopper load should, depending on the site, already be halved and the tyre inflation pressure reduced when soil water content is at around 55 % FC (reference depth 20 cm). A soil compaction index of 0.10 is calculated for the year 2007 at 35 cm soil depth in Aiterhofen, with a soil water content of 74 % FC. Therefore, if soil water content is above 70 % FC, then in order to avoid soil compaction at 35 cm the maximum hopper load should be halved and the tyre inflation pressure reduced. The ground should not be driven over if soil water content is above 80 % FC, even if the hopper load and tyre inflation pressure are reduced.

Table V-3. Soil water contents (SWC, % field capacity - % FC, 0-60 cm soil depth) and calculated Soil Compaction Indices (20 and 35 cm soil depth) of sugar beet harvest for the model farms Aiterhofen and Etzdorf at 100 % hopper load (axle load 26.2 t, tyre inflation pressure 2.7 bar) and 50 % hopper load (axle load 20.8 t, tyre inflation pressure 2.0 bar).

		Aiterhofen[1]					Etzdorf[2]			
		Hopper load [%]					Hopper load [%]			
		100		50			100		50	
	SWC	Soil depth [cm]				SWC	Soil depth [cm]			
Year	[% FC]	20	35	20	35	[% FC]	20	35	20	35
2004	47	0	0	0	0	41	0	0	0	0
2005	56	0	0	0	0	54	0.10	0	0	0
2006	63	0.12	0	0	0	50	0.04	0	0	0
2007	74	0.30	0.10	0.18	0	61	0.20	0	0.08	0
2008	47	0	0	0	0	48	0	0	0	0
2009	41	0	0	0	0	51	0.05	0	0	0
2010	58	0.03	0	0	0	94	0.65	0.35	0.53	0.25
2011	66	0.17	0	0.05	0	62	0.22	0	0.10	0
2012	79	0.38	0.19	0.26	0.07	46	0	0	0	0

[1] precompression stress: 20 cm = 81.3 kPa; 35 cm = 72.4 kPa; own results (Götze et al., 2016a)

[2] precompression stress: 20 cm = 38.9 kPa; 35 cm = 91.2 kPa, unpublished own results,

Increasing harvesting capacity through a higher number of harvesting machines increases the daily area output per region. Accordingly, on days with favourable harvesting conditions (≤ 55 % FC at 20 cm reference depth, or ≤ 70 % FC at 35 cm reference depth) a larger area can be harvested, and in turn the risk of having to harvest areas under unfavourable conditions decreases. The ability to increase harvesting capacity may however be limited for economic reasons. Thus, harvesting sugar beets in periods when soil water contents are lower is one further potential option to reduce the soil compaction risk. In this respect, in future it may prove useful to cultivate winter beets, which are sown in August and harvested in the late summer or autumn of the following year. This could have the effect of bringing the harvest time forward by four to six weeks, without any yield loss. Furthermore, winter beets' more rapid leaf growth in the spring and potentially higher dry matter formation (Hoffmann and Kluge-Severin, 2011) means that higher evapotranspiration, and in turn a lower soil water content compared to spring-sown sugar beet, is likely. However, the winter beet varieties currently available in Central Europe are not practicable because of the risk of frost damage and bolting (Hoffmann and Kluge-Severin, 2011; Reinsdorf and Koch, 2013).

2 Effects of specialised sugar beet crop rotations on sugar beet yield and yield stability

2.1 Discussion of hypothesis

Hypothesis 3: *The yield stability of sugar beet decreases with an increasing concentration of sugar beet in the crop rotation and with a decreasing cropping interval for sugar beet.*

The hypothesis is confirmed to a limited extent, because in this study yield stability does not depend exclusively on cropping concentration or cropping interval (chapter IV). The integration of alfalfa also appeared to have a positive impact on yield stability and yield itself, and a reduction of the cropping interval to one year is possible without any significant yield loss and with high yield stability. In crop rotations with a cropping interval of three or four years, however, it is not possible to separate the effect of the complementary crop alfalfa from the effect of the longer cropping interval. The cultivation of alfalfa in sugar beet crop rotations is currently highly unusual (Buhre et al., 2014), and as such this is not a standard option of intensifying sugar beet crop rotations. With regard to yield level as well as yield stability under the conditions at the Etzdorf long-term field trial, cultivating sugar beet after sugar beet or in monoculture would not be conducive to a sustainable increase in productivity. Here it is necessary to consider the cultivation conditions, especially the selection of varieties. In Etzdorf, even in the final experimental period a variety was consistently grown which is susceptible to nematodes. The yield loss when cultivating in a short crop rotation is thus evident at the site infested with nematodes, and it is possible that cultivating a nematode-tolerant variety would have resulted in a smaller yield loss.

2.2 Potentiallities for reducing sugar beet yield decline in specialised sugar beet rotations

In order to counteract the yield decline associated with concentrated, short crop rotations, Bennett et al. (2012) identify the options listed below, which are discussed in the following in the context of sugar beets:

1. Continued monoculture
2. Extended rotation and break crop
3. Increasing spatial and temporal diversity
4. Management practices

5. Resistance breeding

Continued monoculture

When some crops are grown in monoculture over many years, there are reports of an initial significant yield decline and a subsequent – albeit smaller – yield increase, as a balance is established in the soil between crop rotation pathogens and their pathogens (Bennett et al., 2012). At the Etzdorf long-term field trial, evidence of this was found for the crop rotation pathogen *H. schachtii*, where, 25 years into the experiment, a rise in the parasitization of larvae and eggs by nematophagous fungi in crop rotations with a high concentration of sugar beets had resulted in a decline in the *H. schachtii* population from 2200 eggs and larvae per 100 g of soil to 600 eggs and larvae per 100 g of soil (Mahainparast, 1998). However, there continues to be a considerable difference in yield between sugar beets in monoculture and sugar beets in crop rotation at the Etzdorf long-term field trial, and yield stability is also far lower in monoculture than in crop rotations. For this reason, cultivating sugar beets in monoculture is of no practical relevance, even if it is probable that the effect mentioned above can offset the yield decline to a certain degree.

Extended rotations and break crops

It is known that reducing the cropping concentration and including break crops in crop rotations can increase yield (Bennett et al., 2012). This has also been shown for sugar beets in the older literature (Smukalski and Rogasik, 1977; Wiesner, 1977; Wicke and Urban, 1978; Köppen et al., 1987; Wicke and Matthies, 1990) and is confirmed by recent studies (Hlisnikovsky et al., 2014) and the present investigations. In the context of raising land productivity through specialised sugar beet crop rotations, it is important to integrate those break crops in the crop rotation which permit a short cropping interval and high cropping concentration of sugar beet. Any crops which serve as host plants for diseases and pests that may affect sugar beet yield are therefore unsuitable. Cultivating maize promotes the inoculum potential of and infestation with *Rhizoctonia solani* AG 2-2 IIIB, and sugar beets grown subsequently demonstrate a lower white sugar yield (Kluth and Varrelmann, 2010; Dircks et al., 2014). Brauer-Siebrecht et al. (2016) also report a slightly higher sugar beet dry matter yield after the preceding crop winter wheat than after silage maize, despite the fact that there were no signs of infestation with

R. solani. The own investigations also show an influence of the complementary crops and crops which precede sugar beet on root yield and white sugar yield. When comparing crop rotations with cropping intervals of one and two years, sugar beet yield tends to be higher in the crop rotation SB-WW-SB-Alf-WW than in the crop rotation SB-GM. Even if the low yield seen in the SB-GM crop rotation is attributable in part to the slightly higher sugar beet cropping concentration (50 % compared to 40 %), it is also likely that the preceding and complementary crops – maize and alfalfa – had an effect in the crop rotation, because earlier studies have already found evidence of a positive effect of including alfalfa (Fischer and Liste, 1979; Liste et al., 1990). Hao et al. (2001a) also confirm a higher root yield after grain legumes (*Phaseolus vulgaris* L. and *Pisum sativum* L.) compared to wheat as a preceding crop. However, economic aspects must be considered when selecting complementary crops, and in German sugar beet growing regions wheat is the predominant crop grown before sugar beet (Buhre et al., 2014).

Increasing spatial and temporal diversity

Under this point, Bennett et al. (2012) summarise cultivation methods which permit either the cultivation of at least two different crops on the same area in one year (double cropping) or the cultivation of several different crops at the same time on the same area (intercropping), thereby inhibiting the development cycles of soil-borne pathogens. Such methods are however of less relevance when cultivating sugar beets. When establishing double cropping systems under Central European conditions, the vegetation period of sugar beet is too long to be able to harvest subsequent crops in the same year. From a harvesting perspective, and also given the fact that juvenile sugar beet plants are less competitive, mixed intercropping systems are not relevant. However, it is possible to cultivate sugar beet in row-intercropping systems, where sugar beets are grown in strips with other crops, provided the width of the strip is a whole multiple of the working width of the sowing and harvesting machinery. Against this backdrop, research is currently ongoing into agroforestry systems in order to gain an insight into any effects on soil moisture and sugar beet yield (Mirck et al., 2016).

Another potential solution which is not mentioned by Bennett et al. (2012) is to cultivate catch crops after a cereal as the previous crop. For example, in Germany’s main sugar beet growing regions up to 50 % of the sugar beet acreage is covered with catch crops – usually mustard, fodder radish and phacelia (*Phacelia tanacetifolia* Benth., Buhre et al., 2014). By cultivating nematode-resistant mustard as a catch crop, it is possible to reduce the population of *H. Schachtii* and increase sugar yield (Hauer et al., 2015b). This is however dependent on a high level of biomass production and, therefore, an optimal establishment of the catch crop plants (Hauer et al., 2016). In addition, different catch crops' susceptibility to *R. solani* varieties (Kluth et al., 2010) must also be taken into account when growing in areas infected with *R. solani*, to lower the risk of *R. solani* infection in sugar beets grown later on.

Management practices

More intensive management practices – such as irrigation, additional fertilization with manure, increased N fertilization and application of plant protection products – result in a yield increase in sugar beets grown in monoculture, although it is not possible to compensate the yield loss compared to sugar beets cultivated in crop rotations (Fischer et al., 1981b; Kachel et al., 1981; Fichtner et al., 1984a; Fischer and Duda, 1990; Rychcik and Zawiślak, 2002). It can also be assumed that management practices which are generally able to increase sugar beet yield, such as deep tillage (Liebhard, 1997; Koch et al., 2009) and increased K fertilization (Römer et al., 2004; Damm et al., 2013), also raise and stabilise sugar beet yield in short crop rotations. It should however be considered that more intensive management practices can be associated with increased environmental risks – and such risks should of course be avoided in the context of sustainable agriculture and sustainable intensification (Bennett et al., 2012).

Resistance breeding

In specialised sugar beet crop rotations, the cultivation of varieties which are resistant to crop rotation pathogens can help to enhance yield. The cultivation of nematode-resistant sugar beet varieties is very widespread in infested areas. In southern Hesse and in Rhineland-Palatinate, some 80 % of the sugar beet acreage is already cultivated with nematode-tolerant varieties (Reuther and Lang, 2015). When infested with nematodes, resistant and tolerant varieties achieve higher yield than susceptible varieties (Hauer et al., 2015b). In addition, the cultivation of resistant varieties reduces the population density of *H. schachtii* more strongly than cultivating catch crops (Hauer et al., 2016). Similarly, if the soil is infested with *R. solani*, cultivating corresponding resistant varieties reduces disease severity and increases yield (Buhre et al., 2009; Dircks et al., 2014).

3 Conclusiones

The extent to which specialised sugar beet crop rotations influence the soil organic matter content, the soil structure, and yield and yield stability, depends on the overall cultivation system and the complementary crops in the crop rotation.

In the Etzdorf long-term field trial, under changing cultivation conditions there is no clear evidence of differences in the soil organic matter content of crop rotations with increased cropping concentrations. Furthermore, the current sugar beet cultivation methods in practice could lead to a far lower decline in soil organic matter content than previously reported. This relationship should be investigated further in suitable field trials. Based on current knowledge and considering the results presented, it can be concluded that conventional sugar beet crop rotations do ensure an even humus balance and an adequate supply of organic matter, if each year of sugar beet cultivation is followed by two years of winter wheat cultivation with straw manure.

In crop rotations with sugar beet, there is no increased soil compaction risk compared to crop rotations without sugar beet, as long as the sugar beet harvesting techniques protect the soil (e.g. reduced wheel loads and lowering tyre inflation pressure to the technically permissible minimum) and the soil is not driven over at times when soil water content is high (> 80 % FC). Under these conditions, it can be assumed that specialised sugar beet crop rotations will not have a negative impact on soil fertility as a result of higher soil compaction risks. The sugar beet cropping concentration should therefore be adjusted to a farm’s individual harvesting capacities.

When cultivated in crop rotations with a short cropping interval and high cropping concentration, sugar beet responds with significant yield loss and lower yield stability. However, the results also show that by integrating favourable complementary crops, such as alfalfa, shorter sugar beet crop rotations are possible without any significant yield loss and without a decline in yield stability. Since for economic reasons the integration of alfalfa is not currently practical, it should be examined how feasible it is to increase the cropping concentration by using modern cultivation methods, such as integrating catch crops and cultivating sugar beet varieties which tolerate crop rotation pathogens.

VI Summary

Impact of specialised sugar beet crop rotations on soil fertility parameters and on yield and yield stability of sugar beet

In terms of sustainable intensification, increasing the concentration of crops with a high potential for biomass formation within the crop rotation may result in more efficient land productivity. However, impacts on the environment and yield need to be quantified in order to ensure that any increase in productivity is sustainable. Compared to most crops typically cultivated in Central Europe, sugar beet (SB, *Beta vulgaris* L.) is characterised by a high potential for biomass formation, a favourable energy balance and high land use efficiency. In the context of SB cultivation, there are however often reports of a decline in soil organic matter (SOM) content in the older literature. Furthermore, evidence has been found of adverse effects on the soil structure caused by driving over the soil with heavy SB harvesting machinery when soil water content is high. In addition, there is a significant yield decline if SB are grown in short crop rotations with high cropping concentrations and short cropping intervals, or in monoculture. In this study, the aim was therefore to examine the extent to which specialised SB crop rotations influence soil fertility as well as yield and yield stability. To this end, the following subjects – which have been published in scientific journals – were dealt with in three chapters.

The **first article** (chapter II, Götze et al., 2016b) examines the impact of selected crop rotations with increased SB cropping concentrations on the SOM content at the Etzdorf long-term field trial. Soil samples were taken in 2010 and 2012 in the first crop rotation field of each of the crop rotations SB-SB-WW-WW (WW - winter wheat, *Triticum aestivum* L.), SB-SB-SB-WW, SB-GM (GM - grain maize, *Zea mays* L.) and SB monoculture. The samples were analysed to determine the total organic carbon (TOC) and microbial biomass carbon (MBC) content of the soil as well as the MBC/TOC ratio and the TOC stock (0-30 cm in each case). In addition, humus balances were created (using the software REPRO, reference period twelve years) in order to calculate the soil's supply with organic matter. After 41 trial years, the soil parameters investigated decrease in the order SB-SB-WW-WW, SB-SB-SB-WW, SB monoculture and SB-GM, but differences are small and not statistically significant. On the one hand, the small differences in the soil parameters investigated are attributable to the removal of harvest residues and the routine application of farmyard manure. On the other, the changing cultivation con-

ditions probably also had an effect, which is characterised by an increasing SB yield and decreasing soil tillage intensity throughout the trial period. The humus balances calculated for the reference period also decrease in the order mentioned above, and the differences are in some cases significant. Therefore the humus balance values correlate with the soil parameters but do not reflect the actual demand for organic matter, and in fact overestimate it.

The **second article** (chapter III, Götze et al., 2016a) examines whether the integration of SB in crop rotations influences soil structure, and whether there is an increased soil compaction risk for the crop rotation as a whole. These investigations are based on a crop rotation trial in Aiterhofen, Bavaria, and focus on the crop rotations Mu_SB-WW-WW (Mu - mustard catch crop, *Sinapis alba* L.), SB-WW-Mu_SM (SM - silage maize, *Zea mays* L.), Mu_SM-WW-WW and SM monoculture, which are tested in the trial since 2010. Depending on the cultivation dates, the operation-specific soil compaction risks and the soil compaction risk of the overall crop rotations are modelled at two soil depths (20 and 35 cm). To this end, two scenarios are modelled (100 % and 50 % hopper load for SB and WW harvest) based on assumptions about the current standard equipment used by a model farm. In addition to this, following one complete rotation, the physical soil parameters saturated hydraulic conductivity (k_S) and air capacity (AC) were determined in 2013 and in 2014 at soil depths 2-8 cm, 12-18 cm, 22-28 cm and 32-38 cm in order to quantify the soil structure. The modelled soil compaction risks for the crop rotations including SB are higher at both soil depths than for those without SB. This increased soil compaction risk is primarily attributable to the SB harvest in years with high soil water contents. By halving the hopper load and adjusting the tyre inflation pressure, it is possible to lower the crop rotation's overall soil compaction risk. There are no to low soil compaction risks for all variants in the subsoil (soil depth 35 cm) under these conditions. Soil structure is primarily influenced in the topsoil (2-8 cm) as a result of the cultivation of Mu as a catch crop and WW as a preceding crop. This caused higher k_S, indicating improved structural stability and infiltration capacity. There are no systematic differences in soil structure between variants at other soil depths, or for the parameter AC.

For the first time for SB, apart from yield the **third article** (chapter IV, Götze et al., 2017) also examines the extent to which yield stability declines as the SB cropping concentration increases and the cropping interval for SB decreases. To this end, yield data for the last 13 years of the Etzdorf long-term field trial (2002 until 2014) form the basis of an evaluation. All SB crop rotation fields of the crop rotations examined in the Etzdorf long-term field trial (SB-WW-Alf-Alf-WW (Alf - alfalfa, *Medicago* ssp. L), SB-WW-Alf-WW, SB-Pot-WW (Pot - potato, *Solanum tuberosum* L.), SB-WW-SB-Alf-WW, SB-SB-WW-WW, SB-GM, SB-SB-SB-WW, SB monoculture) are evaluated separately. Both root yield (RY) and white sugar yield (WSY) of SB increase as the SB cropping interval increases or the SB cropping concentration in the crop rotation decreases. A positive effect on RY and WSY is also observed when integrating Alf. Sugar content is lowest in the case of SB monoculture. To assess WSY stability, the coefficient of variation and ecovalence are calculated, and a linear regression analysis of the individual crop rotations' annual yield is performed for the annual average of all crop rotations. Taking these three parameters into account, the crop rotations with a cropping interval of at least two years demonstrate higher yield stability, with WSY also higher, than those rotations where the cropping interval is none or one year. Integrating Alf into the crop rotation means it is also possible to achieve above-average WSY, with high yield stability, in the case of a cropping interval of one year.

Based on the results described and taking into account current knowledge, the following conclusions can be drawn: (i) The standard cultivation methods for SB currently used in practice reduce the SOM content to a lesser extent than previously assumed and a balanced supply of organic matter is ensured, as long as each SB cultivation year is followed by two years of growing WW with straw fertilizer. (ii) Provided that the SB harvesting methods protect the soil (e.g. reduced wheel loads and lowering tyre inflation pressure to the technically permissible minimum) and the soil is not driven over at times when soil water content is more than 80 % of field capacity, specialised SB crop rotations are not associated with an increased risk of soil compaction. (iii) In specialised SB crop rotations, integrating favourable complementary crops such as Alf can counteract a significant yield loss and lower yield stability.

VII Zusammenfassung

Einfluss spezialisierter Zuckerrübenfruchtfolgen auf Parameter der Bodenfruchtbarkeit sowie den Ertrag und die Ertragsstabilität von Zuckerrüben

Im Sinne der nachhaltigen Produktivitätssteigerung kann die Erhöhung des Anteils an Kulturarten mit der höchsten Biomasseproduktion innerhalb der Fruchtfolge die Flächenproduktivität steigern. Allerdings müssen die Auswirkungen auf die Umwelt und den Ertrag quantifiziert werden um eine nachhaltige Produktivitätssteigerung zu gewährleisten. Im Vergleich der meisten für Mitteleuropa typischen Kulturpflanzen sind Zuckerrüben (ZR, *Beta vulgaris* L.) durch ein hohes Biomassebildungspotential, eine günstige Energiebilanz und eine hohe Flächeneffizienz gekennzeichnet. In der älteren Literatur wird bei Anbau von ZR jedoch häufig von einer Abnahme des Gehaltes an organischer Bodensubstanz (OBS) berichtet. Zudem sind Beeinträchtigungen der Bodenstruktur durch das Befahren mit schweren Maschinen zur ZR-Ernte bei hohen Bodenwassergehalten nachgewiesen worden. Darüber hinaus reagieren ZR mit einem deutlichen Ertragsrückgang, wenn diese in enger Fruchtfolge mit hohen Anbaukonzentrationen und kurzer Anbaupause oder Monokultur angebaut werden. In der vorliegenden Arbeit sollte daher geprüft werden, inwiefern spezialisierte ZR-Fruchtfolgen die Bodenfruchtbarkeit sowie den Ertrag und die Ertragsstabilität beeinflussen. Dazu wurden in drei Beiträgen folgende Themen bearbeitet, welche in wissenschaftlichen Zeitschriften publiziert sind.

Im **ersten Beitrag** (Kapitel II, Götze et al., 2016b) wird der Einfluss von ausgewählten Fruchtfolgen mit erhöhten ZR-Anbaukonzentrationen auf den OBS - Gehalt im Dauerfeldversuch Etzdorf untersucht. Dazu wurden in 2010 und 2012 Bodenproben im jeweils ersten Fruchtfolgefeld der Fruchtfolgen ZR-ZR-WW-WW (WW - Winter Weizen, *Triticum aestivum* L.), ZR-ZR-ZR-WW, ZR-KM (KM - Körnermais, *Zea mays* L.) und ZR-Monokultur entnommen und auf den gesamten organischen Kohlenstoff (TOC) Gehalt und den Kohlenstoffgehalt der mikrobiellen Biomasse (MBC) im Boden sowie das MBC/TOC Verhältnis und den TOC Vorrat (jeweils 0-30 cm) untersucht. Zusätzlich wurden fruchtfolgespezifische Humusbilanzen aufgestellt (Humuseinheiten Methode in REPRO, zwölf Jahre Referenzzeitraum) um den Versorgungsgrad des Bodens mit organischer Substanz zu kalkulieren. Nach 41-jähriger Versuchslaufzeit nehmen die TOC und MBC Gehalte, ebenso wie das MBC/TOC Verhältnis und der TOC Vorrat tendenziell in der Reihenfolge ZR-ZR-WW-WW, ZR-ZR-ZR-WW, ZR-Monokultur und ZR-

KM ab. Die Differenzen sind gering und nicht statistisch abzusichern. Die geringen Differenzen der untersuchten Bodenparameter sind zum einen auf die Abfuhr der Erntereste und die routinemäßige Stallmistapplikation zurückzuführen. Zum anderen ist auch ein Einfluss der sich verändernden Anbaubedingungen wahrscheinlich, welche durch einen steigenden ZR-Ertrag und eine abnehmende Intensität der Bodenbearbeitung im Laufe der Versuchslaufzeit charakterisiert ist. Die kalkulierten Humusbilanzen für den Referenzzeitrum nehmen ebenso in der o.g. Reihenfolge ab, wobei die Differenzen teilweise signifikant sind. Daher korrelieren die Humusbilanzen mit den Bodenparametern, der tatsächliche Bedarf an organischer Substanz wird jedoch überschätzt.

Im **zweiten Beitrag** (Kaptitel III, Götze et al., 2016a) wird geprüft ob die Integration von ZR in Fruchtfolgen die Bodenstruktur beeinflusst und ob das Bodenschadverdichtungsrisiko der gesamten Fruchtfolge erhöht wird. Grundlage für diese Untersuchungen bildet ein Fruchtfolgeversuch in Aiterhofen, Bayern. In diesem werden die Fruchtfolgen Senf_ZR-WW-WW (Senf - *Sinapis alba* L., Zwischenfrucht), ZR-WW-Senf_SM (SM - Silomais), Senf_SM-WW-WW and SM - Monokultur seit 2010 geprüft. Auf Grundlage der Anbaudaten wurde zusätzlich das Bodenschadverdichtungsrisiko der fruchtfolgespezifischen Verfahren und der gesamten Fruchtfolgen in zwei Bodentiefen (20 cm und 35 cm) ermittelt. Dafür wurden Modellberechnungen unter der Annahme aktueller und praxisüblicher Maschinenausstattung eines Modellbetriebes für zwei Szenarien (100 % und 50 % Bunkerfüllung für ZR und WW Ernte) durchgeführt. Nach einer vollständigen Rotation wurden in 2013 und 2014 zusätzlich die bodenphysikalischen Parameter gesättigte Wasserleitfähigkeit (k_S) und Luftkapazität (LK) in 2-8 cm, 12-18 cm, 22-28 cm und 32-38 cm Bodentiefe zur Beschreibung der Bodenstruktur bestimmt. Die kalkulierten Bodenschadverdichtungsrisiken sind in beiden Bodentiefen für die Fruchtfolgen mit ZR höher als für die Fruchtfolgen ohne ZR. Dieses höhere Bodenschadverdichtungsrisiko wird maßgeblich durch die ZR-Ernte in Jahren mit hohem Bodenwassergehalt bestimmt. Eine Halbierung der Bunkerfüllung in Kombination mit angepassten Reifeninnendrücken senkt das Bodenschadverdichtungsrisiko der gesamten Fruchtfolge. Unter diesen Voraussetzungen bestehen im krumennahen Unterboden (35 cm Bodentiefe) für alle Varianten keine oder nur geringe Bodenschadverdichtungsrisiken. Die analysierten Bodenstrukturparameter werden hauptsächlich im Oberboden (2-8 cm) beeinflusst. Hier zeigen die Varianten mit WW-Senf Vorfrucht höhere k_S - Werte, was auf eine bessere Strukturstabilität und Infiltrationsleistung dieser Flächen hindeutet. In den anderen Bodentiefen und für den Parameter LK bestehen keine weiteren systematischen Unterschiede zwischen den Varianten.

Im **dritten Beitrag** (Kapitel IV, Götze et al., 2017) wird neben dem Ertrag auch erstmals für ZR geprüft, inwieweit mit zunehmender Anbaukonzentration und abnehmender Anbaupause für ZR die Ertragsstabilität abnimmt. Hierfür wurden die Erträge der letzten 13 Versuchsjahre (2002-2014) im Dauerfeldversuch Etzdorf analysiert. Alle ZR-Fruchtfolgefelder der geprüften Fruchtfolgen (ZR-WW-Luz-Luz-WW (Luz - Luzerne, *Medicago* ssp. L.) ZR-WW-Luz-WW, ZR-Kart-WW (Kart - Kartoffel, *Solanum tuberosum* L.), ZR-WW-ZR-Luz-WW, ZR-ZR-WW-WW, ZR-KM, ZR-ZR-ZR-WW, ZR - Monokultur) wurden dazu separat ausgewertet. Sowohl der Rübenkörperertrag (RE) als auch der Bereinigte Zuckerertrag (BZE) steigen mit zunehmender Anbaupause bzw. abnehmender Anbaukonzentration an ZR in der Fruchtfolge an. Zudem zeigt sich ein positiver Einfluss der Eingliederung von Luz auf den RE und BZE, während der Anbau von ZR in Selbstfolge den geringsten RE und BZE aufweist. Der Zuckergehalt ist in der ZR-Monokultur am niedrigsten. Für die Bewertung der Ertragsstabilität wurden der Variationskoeffizient und die Ökovalenz für den Parameter BZE berechnet sowie eine lineare Regressionsanalyse der Jahreserträge der einzelnen Fruchtfolgefelder zu dem Jahresmittel aller Fruchtfolgefelder durchgeführt. Bei Betrachtung dieser drei Parameter zeigen die Fruchtfolgefelder mit mindestens zwei Jahren Anbaupause eine höhere Ertragsstabilität bei gleichzeitig höherem BZE als die Fruchtfolgen mit keinem und einem Jahr Anbaupause. Durch Integration von Luz in die Fruchtfolge kann auch bei einer Anbaupause von einem Jahr ein überdurchschnittlicher BZE bei hoher Ertragsstabilität erreicht werden.

Aus den genannten Ergebnissen und unter Einbeziehung des aktuellen Wissensstandes können folgende Schlussfolgerungen gezogen werden: (i) Die aktuell praxisüblichen Anbaumethoden für ZR reduzieren den OBS Gehalt in geringerem Maße als bisher angenommen und eine ausgeglichene Versorgung mit organischer Substanz ist gewährleistet, sofern je ZR-Anbaujahr zwei Anbaujahre mit WW und Strohdüngung folgen. (ii) Spezialisierte ZR Fruchtfolgen sind, unter der Vorrausetzung, dass bei der ZR-Ernte bodenschonende Verfahren (z.B. reduzierte Radlasten und Verringerung des Reifeninnendruckes auf das technisch zulässige Minimum) genutzt werden und ein Befahren des Bodens bei Bodenwassergehalten von mehr als 80 % Feldkapazität vermieden wird, nicht mit einem höheren Bodenschadverdichtungsrisiko verbunden. (iii) In spezialisierten ZR-Fruchtfolgen kann durch Integration günstiger Komplementärfrüchte wie Luz einem deutlichen Ertragsverlust und einer geringen Ertragsstabilität entgegengewirkt werden.

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IX Appendix

Appendix 1. Soil parameters (0-30 cm soil depth) and calculated humus balances of different crop rotations at the long-term field trial Etzdorf (TOC - total organic carbon, MBC - microbial biomass carbon, SB - sugar beet, WW - winter wheat, GM - grain maize)

		Crop rotation			
Parameter	Year	SB	SB-SB-SB-WW	SB-GM	SB-SB-WW-WW
TOC content	2010	22.6	22.4	22.7	23.1
[g kg^{-1}]	2012	21.2	21.0	21.6	22.0
MBC content	2010	186.5	187.3	188.7	202.3
[µg C g^{-1}]	2012	160.4	152.5	169.2	170.9
MBC/TOC ratio	2010	0.83	0.84	0.84	0.88
[%]	2012	0.76	0.73	0.78	0.78
TOC stock	2010	97.5	95.9	98.1	98.8
[t ha^{-1}]	2012	90.6	90.7	92.7	93.6
Humus balance	1998-2009	-485.3	-346.6	-489.9	-311.5
[kg humus-C ha^{-1}a^{-1}]	2000-2011	-533.6	-440.8	-538.2	-303.8

Appendix 2. Technical data of the machinery used at the 75 ha model farm Aiterhofen (SB - sugar beet, WW - winter wheat, SM - silage maize).

Operation	No.	Machinery used	Working width [m]
Primary tillage[b]	1	Tractor 120 kW + cultivator	3.0
Seedbed preparation	2	Tractor 120 kW + rotary harrow	3.0
Stubble tillage	3	Tractor 120 kW + cultivator	3.0
SB seeding	4	Tractor 83 kW + 12 row precision drill	6.0
SM seeding	5	Tractor 67 kW + 8 row precision drill	6.0
WW seeding	6	Tractor 120 kW + rotary harrow + drill	3.0
Pesticide application	7	Tractor 67 kW + sprayer 2200l	21.0
N fertilization	8	Tractor 67 kW + sprayer 2200l	21.0
P,K fertilization	9	Tractor 67 kW + spreader 1500l	21.0
SB harvest 100 %[a]	10a	six row self-propelled, two axles	3.0
SB harvest 50 %[a]	10[b]	six row self-propelled, two axles	3.0
SM harvest	11	six row self-propelled forage harvester	4.5
SM transport	12	Tractor 120 kW + trailer 40000 l	4.5
WW harvest 100 %[a]	13a	Combine harvester 200 kW, 8000l	6.0
WW harvest 50 %[a]	13b	Combine harvester 200 kW, 8000l	6.0
Rolling	14	Tractor 67 kW + roll	10.25

[a] hopper load, [b]equal to mustard sowing

Appendix 3. Technical data of the machinery used at the 75 ha model farm Aiterhofen. No. see Appendix 2 (TIP - tyre inflation pressure)

No.	Tractor[a]			Trailer[a]		
	Axle load [kg]	Tyre size	TIP [bar]	Axle load [kg]	Tyre size	TIP [bar]
1	5506	650/65 R 42	0.8			
2	4620	650/65 R 42	0.8			
3	5506	650/65 R 42	0.8			
4	3480	420/85 R 38	0.8			
5	3410	420/85 R 34	0.8			
6	5526	650/65 R 42	0.8			
7	3316	420/85 R 34	0.8	3812	420/85 R 38	0.8
8	3404	420/85 R 34	0.8	4164	420/85 R 38	0.8
9	5848	420/85 R 34	1.4			
10a	26180	1050/50 R 32	2.7			
10b	20790	1050/50 R 32	2.0			
11	7764	650/75 R 32	1.0			
12	6466	650/65 R 42	0.8	8500	600/55 R 22.5	1.6
13a	16400	710/75 R 34	2.0			
13b	14000	710/75 R 34	1.4			
14	2520	420/85 R 34	0.8			

[a] axle with highest load

Appendix 4. Management operations performed in the field trial Aiterhofen and corresponding machinery of the model farm Aiterhofen (No. see Appendix 2) for modelling the soil compaction risk, using the first plot of crop rotation 2 (2.1, Mu_SB-WW-WW) (Mu - mustard, SB - sugar beet, WW - winter wheat) as an example.

Cultivation year	Crop cultivated	Date	Operation	No.
2010	Mu_SB	25/08/2009	N fertilization	8
2010	Mu_SB	26/08/2009	Primary tillage[a]	1
2010	Mu_SB	26/03/2010	Pesticide application	7
2010	Mu_SB	07/04/2010	Seedbed preparation	2
2010	Mu_SB	08/04/2010	SB seeding	4
2010	Mu_SB	10/04/2010	N fertilization	8
2010	Mu_SB	24/04/2010	Pesticide application	7
2010	Mu_SB	30/04/2010	Pesticide application	7
2010	Mu_SB	24/05/2010	Pesticide application	7
2010	Mu_SB	05/06/2010	Pesticide application	7
2010	Mu_SB	14/07/2010	Pesticide application	7
2010	Mu_SB	11/08/2010	Pesticide application	7
2010	Mu_SB	06/09/2010	Pesticide application	7
2010	Mu_SB	12/10/2010	SB harvest	10
2011	WW_1	13/10/2010	Primary tillage	1
2011	WW_1	13/10/2010	WW seeding	6
2011	WW_1	23/02/2011	P,K fertilization	9
2011	WW_1	12/03/2011	N fertilization	8
2011	WW_1	09/04/2011	Pesticide application	7
2011	WW_1	11/04/2011	N fertilization	8
2011	WW_1	28/04/2011	Pesticide application	7
2011	WW_1	20/05/2011	N fertilization	8
2011	WW_1	20/05/2011	Pesticide application	7
2011	WW_1	31/05/2011	N fertilization	8
2011	WW_1	11/08/2011	WW harvest	13
2012	WW_2	26/08/2011	Stubble tillage	3
2012	WW_2	27/09/2011	Primary tillage	1
2012	WW_2	30/09/2011	WW seeding	6
2012	WW_2	20/03/2012	N fertilization	8
2012	WW_2	21/03/2012	Rolling	14
2012	WW_2	19/04/2012	Pesticide application	7
2012	WW_2	23/04/2012	N fertilization	8
2012	WW_2	26/04/2012	Pesticide application	7
2012	WW_2	15/05/2012	N fertilization	8
2012	WW_2	24/05/2012	N fertilization	8
2012	WW_2	02/06/2012	Pesticide application	7
2012	WW_2	13/07/2012	Pesticide application	7
2012	WW_2	01/08/2012	WW harvest	13

Appendix 5. Yield parameters and technological quality of sugar beet at the long-term field trial Etzdorf (RY - root yield, SC - sugar content, K - potassium, Na - sodium, AmN - amino-Nitrogen, SML - standad molasses loss, WSC - white sugar content, WSY - white sugar yield).

Year	RY [t ha^{-1}]	SC [%]	K	Na	AmN	SML [%]	WSC [%]	WSY [t ha^{-1}]
			[mmol (100 g)$^{-1}$ beet]					
Crop rotation field 1.1. (winter wheat-alfalfa-winter wheat)-sugar beet								
2002	48.45	15.61	4.35	2.80	1.49	2.30	13.31	6.47
2003	66.16	17.76	4.21	2.65	1.41	2.24	15.52	10.28
2004	53.90	18.25	5.58	2.68	4.64	3.18	15.07	8.10
2005	48.83	16.59	5.17	3.53	3.18	2.88	13.70	6.69
2006	61.54	15.94	5.18	3.16	1.99	2.56	13.38	8.22
2007	54.65	16.71	5.33	2.79	1.79	2.48	14.23	7.77
2008	60.27	18.46	4.39	2.06	1.39	2.18	16.28	9.81
2009	73.31	17.00	4.56	2.35	1.60	2.29	14.71	10.78
2010	51.27	17.48	4.66	3.19	2.38	2.59	14.88	7.63
2012	92.56	15.87	3.81	2.76	1.90	2.32	13.55	12.53
2013	60.49	19.59	3.97	1.99	2.07	2.29	17.30	10.50
2014	46.33	17.52	4.02	6.04	2.30	2.84	14.68	6.80
Crop rotation field 2.1. (sugar beet winter wheat-winter wheat)-sugar beet								
2002	47.69	16.23	4.52	2.77	2.53	2.56	13.67	6.52
2003	64.60	18.17	4.33	2.38	1.53	2.25	15.92	10.27
2004	56.30	17.69	4.98	2.14	4.29	2.96	14.73	8.29
2005	50.57	16.62	4.33	2.46	2.21	2.42	14.19	7.19
2006	51.18	16.07	5.16	2.41	1.79	2.41	13.65	6.99
2007	55.51	17.29	5.47	1.86	0.88	2.17	15.12	8.39
2008	46.61	19.61	4.32	1.29	1.48	2.11	17.50	8.15
2009	64.18	17.45	4.08	1.31	1.46	2.07	15.37	9.87
2010	45.08	18.10	4.96	1.76	2.32	2.44	15.66	7.06
2012	82.27	15.68	4.16	1.97	2.33	2.37	13.31	10.94
2013	51.08	18.60	3.82	1.51	2.29	2.27	16.33	8.33
2014	37.75	18.24	3.79	2.31	1.74	2.23	16.01	6.09

Appendix 5. Continuaiton.

Year	RY [t ha^{-1}]	SC [%]	K	Na [mmol (100 g)$^{-1}$ beet]	AmN	SML [%]	WSC [%]	WSY [t ha^{-1}]
Crop rotation field 2.2. (winter wheat-winter wheat-sugar beet)-sugar beet								
2002	30.68	16.28	4.52	2.21	1.98	2.36	13.92	4.28
2003	58.58	18.16	4.08	2.33	1.82	2.28	15.87	9.30
2004	44.43	18.94	5.98	2.23	4.37	3.11	15.82	7.03
2005	42.35	16.10	4.51	2.23	1.92	2.35	13.75	5.83
2006	35.51	15.61	4.59	2.17	1.81	2.32	13.28	4.72
2007	40.23	17.57	5.61	1.55	1.23	2.23	15.33	6.16
2008	48.84	18.77	4.61	1.75	0.60	1.99	16.78	8.16
2009	47.66	17.07	4.05	1.08	2.22	2.23	14.83	7.07
2010	30.44	17.61	5.04	1.71	1.96	2.36	15.24	4.65
2012	77.32	15.91	4.53	2.10	2.02	2.36	13.55	10.47
2013	53.34	18.62	3.83	1.64	2.10	2.24	16.38	8.74
2014	17.78	17.52	4.17	1.29	1.72	2.15	15.37	2.81
Crop rotation field 3.1. (potato-winter wheat)-sugar beet								
2002	54.58	16.64	4.13	2.42	1.98	2.34	14.29	7.80
2003	60.14	18.49	3.62	2.25	2.08	2.28	16.21	9.75
2004	54.15	18.72	5.28	2.98	5.00	3.27	15.45	8.36
2005	50.17	16.73	4.40	2.70	2.21	2.46	14.26	7.15
2006	53.97	16.01	4.43	2.31	1.87	2.33	13.67	7.37
2007	50.31	17.09	5.20	2.32	1.30	2.29	14.79	7.47
2008	53.13	19.33	4.24	1.26	1.39	2.07	17.26	9.16
2009	68.78	17.28	3.93	1.01	2.12	2.18	15.10	10.38
2010	42.73	18.14	4.27	2.34	2.25	2.41	15.73	6.72
2012	79.06	16.12	3.98	1.60	2.12	2.26	13.86	10.94
2013	54.20	19.44	3.60	1.30	2.03	2.15	17.28	9.40
2014	30.91	18.10	4.06	2.42	1.71	2.27	15.83	4.89

Appendix 5. Continuation.

Year	RY [t ha^{-1}]	SC [%]	K	Na	AmN	SML [%]	WSC [%]	WSY [t ha^{-1}]
			[mmol (100 g)$^{-1}$ beet]					
Crop rotation field 4.1. (winter wheat-alfalfa-alfalfa-winter wheat)-sugar beet								
2002	52.12	16.40	4.26	2.79	1.77	2.35	14.04	7.34
2003	71.41	17.46	3.80	3.08	1.71	2.31	15.14	10.82
2004	59.92	17.39	5.65	3.20	5.32	3.42	13.98	8.38
2005	52.33	16.48	4.56	3.88	2.58	2.71	13.76	7.19
2006	62.91	16.00	5.11	3.12	1.97	2.54	13.47	8.48
2007	57.06	17.00	5.25	2.57	1.39	2.35	14.65	8.36
2008	53.37	18.27	4.67	2.43	1.49	2.29	15.98	8.50
2009	71.20	17.32	4.11	2.27	1.28	2.15	15.17	10.81
2010	56.16	17.21	4.41	3.40	2.40	2.59	14.61	8.21
2012	96.13	15.70	4.15	2.77	2.09	2.41	13.29	12.75
2013	68.16	18.88	3.71	2.31	2.01	2.28	16.60	11.30
2014	33.89	17.86	3.52	3.15	1.65	2.27	15.59	5.31
Crop rotation field 5.1. (sugar beet-sugar beet-winter wheat)-sugar beet								
2002	44.24	16.55	4.37	1.67	1.96	2.27	14.27	6.32
2003	60.20	17.91	3.50	1.65	1.79	2.13	15.78	9.51
2004	52.80	19.17	5.40	1.60	4.88	3.09	16.08	8.51
2005	46.76	17.87	4.55	1.74	2.34	2.39	15.48	7.23
2006	48.47	16.29	4.41	1.40	2.00	2.25	14.03	6.80
2007	42.99	17.25	5.22	1.24	1.59	2.24	15.02	6.46
2008	53.85	18.97	4.29	0.70	2.34	2.24	16.72	9.02
2009	66.11	17.35	4.06	0.88	2.29	2.22	15.13	10.01
2010	39.93	19.00	4.52	0.93	1.90	2.19	16.81	6.72
2012	72.98	16.14	4.28	1.06	1.65	2.12	14.02	10.18
2013	54.80	18.27	3.78	1.10	2.31	2.22	16.05	8.79
2014	34.33	18.61	4.09	1.11	2.10	2.21	16.40	5.66

Appendix 5. Continuation.

Year	RY [t ha^{-1}]	SC [%]	K	Na [mmol (100 g)$^{-1}$ beet]	AmN	SML [%]	WSC [%]	WSY [t ha^{-1}]
Crop rotation field 5.2. (sugar beet-winter wheat- sugar beet)-sugar beet								
2002	34.01	17.19	4.73	2.01	2.12	2.40	14.80	5.02
2003	53.57	17.49	3.71	1.23	1.93	2.13	15.35	8.23
2004	48.23	18.63	5.35	1.51	3.64	2.77	15.86	7.64
2005	44.02	16.80	4.72	1.64	2.12	2.35	14.45	6.37
2006	42.90	15.94	4.50	1.36	1.88	2.23	13.70	5.86
2007	38.12	17.68	5.27	0.94	1.39	2.16	15.52	5.91
2008	44.73	18.22	4.12	0.96	2.45	2.28	15.94	7.13
2009	56.46	17.62	4.00	0.86	1.88	2.11	15.50	8.78
2010	35.09	18.27	4.80	1.24	2.38	2.37	15.90	5.56
2012	71.28	16.39	3.92	1.10	1.60	2.06	14.33	10.20
2013	45.91	17.71	3.41	1.04	1.72	2.02	15.69	7.28
2014	16.46	15.83	4.62	1.29	2.01	2.27	13.56	2.39
Crop rotation field 5.3. (winter wheat- sugar beet-sugar beet)-sugar beet								
2002	37.26	16.53	4.28	1.57	1.90	2.24	14.29	5.34
2003	56.84	18.62	3.74	1.46	2.14	2.21	16.41	9.32
2004	44.36	18.45	5.15	1.21	3.91	2.78	15.67	6.95
2005	38.46	16.52	4.29	1.79	2.03	2.29	14.23	5.48
2006	45.09	16.11	4.54	1.29	2.00	2.26	13.85	6.25
2007	37.05	17.82	5.34	1.14	2.00	2.33	15.48	5.73
2008	34.20	18.76	4.18	0.83	1.44	2.02	16.74	5.73
2009	50.56	17.42	3.85	0.86	2.20	2.17	15.24	7.71
2010	38.92	18.37	4.77	1.14	2.49	2.38	15.99	6.26
2012	74.64	15.97	3.96	1.18	1.92	2.16	13.82	10.30
2013	35.87	17.70	3.60	1.06	2.03	2.12	15.58	5.55
2014	17.45	14.50	4.06	1.21	1.61	2.10	12.40	1.98

Appendix 5. Continuation.

Year	RY [t ha^{-1}]	SC [%]	K [mmol (100 g)$^{-1}$ beet]	Na	AmN	SML [%]	WSC [%]	WSY [t ha^{-1}]
Crop rotation field 6.1. (winter wheat-sugar beet-alfalfa-winter wheat)-sugar beet								
2002	50.98	16.10	4.18	2.66	2.39	2.47	13.62	6.94
2003	65.34	18.08	3.57	2.69	1.76	2.25	15.83	10.34
2004	54.33	18.39	5.80	3.08	5.55	3.47	14.91	8.10
2005	48.10	17.36	4.67	2.88	2.61	2.61	14.75	7.09
2006	55.72	15.71	4.67	3.21	1.87	2.47	13.23	7.39
2007	51.61	16.96	5.08	2.22	1.70	2.36	14.59	7.52
2008	64.10	18.47	4.03	1.66	1.39	2.09	16.37	10.48
2009	68.51	17.81	4.20	1.63	1.85	2.22	15.59	10.68
2010	40.89	18.67	4.74	2.37	2.14	2.44	16.23	6.62
2012	88.77	15.86	4.29	2.14	2.43	2.43	13.43	11.90
2013	53.99	18.21	3.66	2.70	2.23	2.38	15.83	8.56
2014	34.56	17.64	3.91	2.81	1.87	2.33	15.30	5.28
Crop rotation field 6.3. (alfalfa-winter wheat-sugar beet-winter wheat)-sugar beet								
2002	46.00	16.83	4.36	2.80	2.18	2.46	14.37	6.61
2003	64.34	18.29	3.85	2.83	1.90	2.33	15.96	10.26
2004	51.98	18.06	5.45	2.59	4.76	3.18	14.88	7.75
2005	55.81	16.58	4.62	2.95	2.36	2.55	14.02	7.82
2006	56.41	15.87	4.68	2.80	1.75	2.40	13.47	7.60
2007	53.91	17.33	5.16	1.91	1.80	2.36	14.97	8.07
2008	48.41	18.92	4.42	1.57	1.54	2.17	16.75	8.11
2009	67.03	17.37	4.05	1.58	2.13	2.26	15.10	10.17
2010	42.11	18.23	4.43	2.07	2.05	2.35	15.88	6.69
2012	87.15	15.92	4.53	2.24	1.62	2.28	13.64	11.87
2013	59.74	19.46	3.58	1.78	1.97	2.19	17.26	10.28
2014	32.56	17.87	4.20	2.32	1.94	2.32	15.55	5.06

Appendix 5. Continuation.

Year	RY [t ha^{-1}]	SC [%]	K	Na	AmN	SML [%]	WSC [%]	WSY [t ha^{-1}]
			[mmol (100 g)$^{-1}$ beet]					
Crop rotation field 7.1. (grain maize)-sugar beet								
2002	49.92	16.85	3.84	1.84	2.11	2.27	14.58	7.28
2003	55.18	17.87	3.64	1.53	1.95	2.16	15.70	8.66
2004	54.22	18.49	5.12	1.69	4.67	3.01	15.47	8.39
2005	44.04	16.80	4.24	1.72	2.11	2.30	14.51	6.46
2006	53.56	16.83	4.36	1.90	1.89	2.28	14.54	7.78
2007	48.35	17.47	4.62	1.28	2.23	2.32	15.15	7.33
2008	56.71	18.68	4.04	1.03	1.81	2.12	16.56	9.38
2009	60.18	17.35	3.72	0.89	2.04	2.12	15.23	9.16
2010	44.27	18.71	4.26	1.15	2.22	2.26	16.45	7.27
2012	73.44	15.99	3.95	1.30	1.61	2.09	13.89	10.20
2013	58.36	19.43	3.46	1.10	1.71	2.03	17.40	10.19
2014	30.42	18.46	3.33	1.59	1.59	2.05	16.41	5.05
Crop rotation field 8.1. sugar beet monoculture								
2002	36.87	17.35	4.46	1.37	1.88	2.23	15.12	5.59
2003	57.10	18.41	3.60	0.97	1.86	2.07	16.33	9.33
2004	47.55	19.72	5.24	1.38	4.02	2.84	16.89	8.05
2005	42.68	16.74	4.44	1.57	2.02	2.29	14.46	6.16
2006	44.96	16.65	4.23	1.13	2.23	2.26	14.40	6.48
2007	32.53	17.42	5.34	0.98	1.93	2.30	15.12	4.94
2008	50.32	17.48	4.42	1.47	1.52	2.15	15.33	7.67
2009	50.52	17.22	3.92	0.66	1.72	2.04	15.18	7.64
2010	28.80	15.77	5.09	0.89	2.30	2.35	13.43	3.63
2012	54.66	9.29	4.29	1.07	1.48	2.08	7.39	4.35
2013	39.61	9.41	4.66	1.24	2.08	2.28	8.18	4.22
2014	15.93	14.22	4.26	1.13	1.98	2.20	12.01	2.00

X Curriculum Vitae

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XI Eidesstattliche Erklärung / Declaration under Oath

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

I declare under penalty of perjury that this thesis is my own work entirely and has been written without any help from other people. I used only the sources mentioned and included all the citations correctly both in word or content.

24. November 2016

Datum / Date

Unterschrift des Antragstellers / *Signature of the applicant*

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