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Master Thesis:

Nutrient and soil organic matter budgets of the stockless organic research farm Kleinhohenheim

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Summary

Organic agriculture relies on a steady nutrient and organic matter supply to its fields to ensure soil fertility. Nutrients should be supplied in a sustainable manner which entails the provision of nutrients through nutrient recycling within the farm or importing nutrients from natural sources. Stockless organic farms (OFs) cannot recycle nutrients within the farm because they do not possess livestock and for nutrient recycling manure of livestock is essential. Therefore, stockless OFs often have P and K deficits. These nutrient deficits could be alleviated by importing organic fertilizers. Nutrient farm-gate and field budgets of the research farm Kleinhohenheim were calculated to see if the current stockless management with no fertilizer inputs results in nutrient deficiencies. The average nutrient farm-gate budget was positive for N (+ 10 kg ha^{-1} year^{-1}) and negative for P (- 9 kg ha^{-1} year^{-1}) and K (- 28 kg ha^{-1} year^{-1}). The P and K nutrient deficit was greater when the share of N coming from biological N fixation was higher. The average nutrient field budget was positive for N and negative for P. When fields were fertilized with clover grass silage some fields had positive P and K field budgets. Surprisingly, the average nutrient field budget for K was positive (+ 27 kg ha^{-1} year^{-1}) which indicated an unintended K input included in field budget calculations. When nutrient farm-gate budgets were calculated with three fertilizer inputs (compost, biogas digestate and struvite) all results showed positive farm-gate P and K nutrient budgets, making them a suitable future strategy to alleviate nutrient deficits and maintain soil fertility. More research about their suitability (nutrient availability, accessibility, economic viability) for Kleinhohenheim is needed. Soil organic matter (SOM) also plays a crucial role in maintaining the soil fertility by providing nutrients to the crops and improving soil structure. Stockless OFs supply mainly straw as organic matter (OM) to the fields which has a lower SOM reproduction capacity than farmyard manure which is why they might struggle to achieve positive SOM budgets. Furthermore, other studies found that SOM budgets were higher on farms with livestock because manure was applied. But SOM farm-gate and field budgets of Kleinhohenheim were positive (+ 141 and + 204 kg C ha^{-1} year^{-1}) indicating a sufficient supply of OM to the farm and its fields. Depending on the evaluation system for SOM budgets they could be evaluated as optimal or high. Still, the supply of OM could be further increased to stop the trend of declining SOM content as detected from the soil analyses. SOM budgets can only evaluate the supply of OM to the farm but cannot predict SOM content changes in the soil which is why future research should monitor the changes of SOM content through long-term experiments.

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List of abbreviations

Chemical elements are abbreviated by their chemical symbol.

The standard abbreviations of the International System of Units (SI) are used.

Other abbreviations:

AD	Anaerobic digestion
BD	Biogas digestate
BNF	Biological Nitrogen Fixation
C_{dec}	Decomposable carbon
CG	Clover grass
CGS	Clover grass silage
C_i	Inert carbon
C_{org}	Organic carbon
FM	Fresh matter
FYM	Farmyard manure
ha	Hectare
KH1 - KH8	Labels for Kleinhohenheim fields
OA	Organic agriculture
OF	Organic farm
OM	Organic matter
SOC	Soil organic carbon
SOM	Soil organic matter
SOM-RC	Soil organic matter reproduction capacity

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1. Introduction

Current crises such as climate change and the biodiversity crisis led to the formation of the European Green Deal which entails the Farm to Fork Strategy. This strategy aims to increase the agricultural area farmed under organic principles up to 25 % until 2030 to create a climate neutral and biodiverse food production system (EU Commission COM/2021/141 final/2). Alongside the environmental protection measures, another important part of the Farm to Fork Strategy aims to safeguard food security for everyone whereas a bigger part of the agricultural food sector produces organically. So, to be able to call an organic food system truly "sustainable" not only environmental protection measures must be implemented but also food security must be ensured.

To achieve sustainable organic agriculture (OA), current problems of OA have to be solved. One of the biggest challenges of OA are lower yields compared to conventional agriculture, which is especially the case for arable crops (Seufert et al., 2012). The main reason for lower yields is the lower N availability for plants (Berry et al., 2002). Despite the goal of realizing higher yields, there are even more fundamental problems regarding soil fertility in OA. In theory, the soil remains fertile with the right nutrient and SOM management. In reality many arable farms struggle with nutrient depletion, especially for the nutrients P and K (Reimer et al., 2020a). This nutrient depletion must be overcome for a sustainable OA. That is why chapter 1 of this thesis assesses the challenges with and solutions for a sustainable nutrient and soil organic matter (SOM) management in arable OA. These two factors are crucial for soil fertility and an overall sustainable arable OA.

1.1. Nutrient management in arable organic agriculture

The production of arable OA relies on its soil fertility which means the ability of the soil to provide nutrients for the crops (IFOAM, 2017). Soil fertility gets diminished over time by cultivating and selling crops (also called "output" of the farm). Therefore, OA needs to maintain its soil fertility by supplying nutrients (also called "input" of the farm) to its fields for long-term sustainability.

Watson et al. (2002) list numerous management practices which play a key role in soil fertility management. Firstly, a crop rotation with leguminous crops helps supply the crops with N due to the biological Nitrogen fixation (BNF) and thus not only increases the N content but also the SOM content. Secondly, crop residues can be a source for reproducing SOM and for nutrients. Lastly, the management of manures and supplementary fertilizers is essential for long-term soil fertility. With livestock and their manures nutrients can be distributed between the fields more evenly and can increase the yield of profitable cash crops while also closing nutrient cycles. Specific mineral fertilizers which are permitted in OA should be used where the nutrients cannot be replenished otherwise to maintain the soil fertility (Watson et al., 2002).

Another guide for sustainably maintaining soil fertility and supplying sufficient nutrients to the fields are "The Principles of Organic Agriculture" created by the International Federation of Organic Agriculture Movements (IFOAM – Organics International). These principles imply that nutrients should come from natural sources such as BNF (via legumes), compost or animal manures. Nutrients should also be provided by recycling nutrients within the farm by using animal manures or compost as a fertilizer, so OA uses its resources as efficiently as possible and does not rely on external inputs (such as mineral or synthetic fertilizers) (IFOAM, 2017). This way, nutrient cycles would be closed but in reality the outputs of the farm (plant and animal products) mostly leave the farm towards urban environments. This creates an unidirectional flow of nutrients away from the farm which makes nutrient recycling within the farm impossible (Reimer et al., 2020a). To have a better chance of closing nutrient cycles Nesme et al. (2012) suggests to consider nutrient recycling on a bigger, regional scale which includes returning waste streams from urban environments back to the farms.

Oelofse et al. (2010) confirmed the suggestions of Watson et al. (2002) that external fertilizers can help organic farms (OFs) to achieve a positive nutrient budget. Most OFs studied by Oelofse et al. had a nutrient surplus because they just substituted the previously used mineral fertilizers with organic fertilizers. The problem with this is the dependency of OFs on an external nutrient supply (which might even come from non-organic sources in form of permitted mineral fertilizers or from conventional farms) which is not in line with the OA principles (IFOAM, 2017). The external inputs should only supplement nutrient cycling within the farm and come from organic sources (Oelofse et al., 2010).

As described by IFOAM (2017) and Watson et al. (2002) the recycling of nutrients within the farm is a core part of OA and is best done by animals and its manures. Anglade et al. (2015b) found that 36 % of N input to crop land comes from animals which graze on grasslands and produce manure which is applied to the fields. For stockless OFs nutrient recycling and supplying enough N input to the fields poses a problem because stockless OFs do not possess any livestock due to the specialization of many farms in the last decades and therefore have very limited possibilities to recycle nutrients within the farm (Anglade et al., 2015b; Watson et al., 2002). Even though Nesme et al. (2012) claims that a balanced farm P budget is more dependent on the fertilizer import strategy of the farmer than the stocking density, Reimer et al. (2020b) and Foissy et al. (2013) found a negative relation between stocking density and nutrient (especially N) budgets.

The literature shows that arable stockless OFs have overall (whether they are positive or negative) lower nutrient budgets for N, P and K compared to dairy/beef or vegetable OFs (Reimer et al., 2020b). Vegetable OFs had the highest nutrient surplus for N and P (for K dairy/beef OFs had the highest surplus) compared to stockless arable OFs because of the high nutrient inputs through animal manures (Tittatelli et al., 2016). Stockless OFs had lower but still positive N budgets because they can meet their N demands through BNF (Reimer et al., 2020a). Nutrient budgets for P and K on the other hand were negative because of a lack of P and K inputs in stockless OFs and they are almost always negative when more than 60 % of N inputs came from BNF (Reimer et al., 2020a). This correlation can be explained by the requirement of nitrogen fixing plants (e.g. red clover) for nutrients such as P and K to be able to grow sufficiently and to fixate N (Römer and Lehne, 2004). For OFs animal feed is one of the largest N and P inputs and when it is missing in stockless OFs the only nutrient that can be substituted is N through BNF. Other nutrients such as P and K can only be supplied by importing fertilizers such as rock phosphate, compost, manure or others (Nesme et al., 2012). When no external fertilizers for P and K replenishment are used, there is a constant mining of P and K from these farms through the export of cash crops and the additional plants grown for BNF worsen this nutrient deficit (Reimer et al., 2020a).

Nesme et al. (2012) showed that nutrient budgets can be improved by importing fertilizer. Especially stockless OFs would need to compensate their nutrient demand for P and K by importing organic fertilizers such as animal manures or other fertilizers derived from animals (e.g. meat and bone meal) as well as plant-based fertilizers (Reimer et al., 2020a). Even though it is permitted in OA to import external fertilizers such as animal manures (even from conventional farms), this violates the IFOAM principles (2017) of closed nutrient cycles and results in a dependency of OFs (especially stockless OFs) on conventional agriculture (Reimer et al., 2020a). This is why there is an ongoing discussion if manure imports and other contentious inputs should be phased out but to be able to do so there have to be sufficient fertilizer alternatives to substitute the manure.

1.2. Possible fertilizers for nutrient provision

The primary aim of OA is to supply nutrients to the fields through internal nutrient cycling. A farm which supplies most of its N needs with nutrient recycling within the farm and imports only small or no amounts of external inputs shows very low N surpluses. Regardless of the farm type (mixed or stockless OFs) this low N surplus also results in low N yields (Anglade et al., 2015b). When the nutrient demand cannot be met with nutrient recycling, sustainable external organic fertilizers which are in line with OA principles (closing nutrient cycles) should be imported to ensure high yields (IFOAM, 2017).

Zikeli et al. (2022) summarized possible alternative fertilizers and their characteristics for OA. The list includes compost, biogas digestate (with substrates from an OF or urban environments), clover grass (CG) pellets and silage, bean powder, nettle liquid, tofu whey and many more. Not all of these fertilizers are relevant for arable farming but some could be interesting alternatives, especially when it comes to closing nutrient cycles on a regional scale (and between urban environments and farms) and using fertilizers which adhere to organic principles. On this basis three fertilizers which fulfil these requirements and may be suitable for Kleinhohenheim were chosen to calculate nutrient budget scenarios: compost (from biowaste), biogas digestate (BD) and struvite. With these scenario budget calculations it was investigated if or which fertilizer could improve the nutrient budgets of the current management of Kleinhohenheim (explained in detail in chapter 2.3.3).

1.2.1. Compost

Compost is a fertilizer which can be used to close nutrient cycles and increase soil fertility. Compost application is known to improve soil properties such as SOM and nutrient content of the soil (Adugna, 2016). This research only focused on and investigated the nutrient content improving qualities of compost and not the SOM improvement through compost. There are different types of composts with different properties (e.g. household waste, green manure, cattle or poultry manure compost). They differ regarding their pH, organic carbon content, nutrient availability and texture or particle size (Duong et al., 2011; Wilson et al., 2019). For this research household biowaste compost was chosen with a nutrient content of 0,94 % N, 0,2 % P and 0,63 % K (Möller and Schultheiß, 2014) (Table 4). The effect of composts on soil properties and plant growth was dependent on the texture of the compost (fine or coarse) with fine composts having a greater effect than coarse composts because fine composts have a greater surface area which microorganisms can access and degrade much faster than coarse composts (Duong et al., 2011). Mature composts such as municipal source separated biowaste compost achieved small increases in N availability and increases in K availability but not P availability. Immature composts even immobilized N and would only be suitable for application when used together with mineral N fertilizers to compensate the less available N (Wilson et al., 2019). Another pot experiment also found most composts to increase the availability of N and P in two different soils (Duong et al., 2011). It is interesting to note, that the N and P availability in the composts did not suggest the effect of the compost on the actual N and P availability in the soil. The N and P availability in the soil is determined by mineralization and mobilization rates of the nutrients which varies between composts and soils (Duong et al., 2011).

1.2.2. Biogas digestate

BD is the "by-product" remaining after anaerobic digestion (AD). The main product of AD is biogas which consists mainly of methane which is why AD is also called "methanogenesis". From the beginning, AD was a holistic approach of using the energy and the nutrients of waste streams (Braun, 2007). Therefore, BD as a nutrient-rich product of AD is optimal for closing nutrient cycles. According to Möller and Schultheiß (2014) BD contains 0,55 % N, 0,1 % P and 0,44 % K (Table 4).

It was shown that BD from AD can be used as a fertilizer and increase plant growth and fruit production (Lee et al., 2021). The higher the BD concentrations in the fertilizer the higher was the increase in plant growth (Vanegas and Bartlett, 2015). This plant growth enhancing effect of BD can be explained by the nutrient provision through BD and a short-term increase of nitrification rate of microorganisms by BD (compared to manure) which increases N availability to the plants. The N availability (i.e. soluble inorganic forms of N) of BD is also better than the N availability of manure because during the AD the nutrients are mineralized (Gómez-Brandón et al., 2016). This makes BD a viable option for N fertilization which might help Kleinhohenheim to increase yields because N supply to the crops at the optimal time is a great yield-limiting factor (Berry et al., 2002). It was also shown, that the AD of CG and other crop residues had an increasing effect on the DM yield and N content of wheat grains and was therefore a much more potent fertilizer than just leaving the CG and crop residues on the fields (Stinner et al., 2008). So, even though the total available N in CG (and other crop residues) and BD is the same, the N availability is higher in BD because most of the available N in BD is "mobile" and therefore better plant available. Furthermore, a more even distribution of N within the crop rotation could be achieved using BD as a fertilizer because a more targeted N supply in space and time was possible (Stinner et al., 2008).

1.2.3. Struvite

Struvite is a crystal salt which precipitates from sewage sludge as magnesium-ammonium-phosphate (Wu et al., 2022). It can then be used as a fertilizer which is optimal for closing nutrient cycles between urban environments and farms (Steinmetz et al., 2023). The use of struvite as a fertilizer is permitted in OA since February 2023 according to the European union regulation (Regulation (EU) 2023/121 Annex II OJEU L16 from 16th February 2023). Struvite has very little heavy metal contents and biological residues, so it does not pose any risks to humans or the environment when being used as a fertilizer (Ronteltap et al., 2007). Struvite contains mainly P (11,6 %), some N (5,4 %) and very little K (0,03 %) (Rittl et al., 2019) (Table 4).

That struvite as a P fertilizer has a significant effect on crop growth was demonstrated by Schmoock (2017). In another 21-day pot experiment the plant (rye) uptake of P from struvite was the same as for triple and superphosphate suggesting a similar plant availability of struvite compared to mineral P fertilizers even though struvite as a Mg-phosphate has a lower water solubility (Römer, 2006). There was a slight trend suggesting that P availability of Mg-phosphates (struvite) is even higher than of Ca-phosphates which might be due to the additional N input for plants included in struvite (Römer, 2006). Another pot experiment showed that there were no significant P offtake differences between fertilization with monocalcium phosphate and struvite recovered from sewage sludge, suggesting a similar P availability of the fertilizers to the plants (Johnston and Richards, 2003). Hertzberger et al. (2020) showed that P uptake and aboveground biomass of plants was similar for struvite fertilized plants to ammonium phosphate or superphosphate fertilized plants. Biomass was even higher with struvite fertilization compared to ammonium phosphate or superphosphate fertilization when soil pH was lower than six. The higher the pH the less crop response after struvite fertilization was measured which showed that the efficacy of struvite as a P fertilizer depends on soil pH (Hertzberger et al., 2020). But other field experiments evidenced that organic wheat and forage yields increased with increasing struvite application even in alkaline soil (Thiessen Martens et al., 2022). According to Hertzberger et al. (2020), struvite fertilization had the same effect on aboveground biomass or P uptake independent of the soil type and the particle size of the applied struvite. On the other hand, Nongqwenga et al. (2017) found the effectiveness of struvite to be dependent on the soil type.

All three fertilizers have the potential to compensate potential nutrient deficits. A critical examination of the actual suitability of the fertilizers for Kleinhohenheim is discussed in chapter 4.4.

1.3. Soil organic matter in arable organic agriculture

1.3.1. Definition of soil organic matter

SOM is defined as dead organic matter (OM) from plant, animal or even (anthropogenic) synthetic origin in the mineral soil and plays a key role for achieving sustainable soil fertility in OA (Amelung et al., 2018). SOM consists of many fractions which are often classified according to their characteristics such as degradation speed (Shepherd et al., 2002). There are many ways to classify SOM into so called “pools” but only two pools are described by the BLE (2022) and Körschens et al. (1998). According to the BLE (2022) most of the SOM consists of permanent SOM (up to 90 %) which is very hard to degrade for the microorganisms and therefore has a slow turnover rate. The other 10 % SOM are fast degrading OM components and are responsible for most of the nutrient provision (BLE, 2022). Körschens et al. (1998) groups the total organic carbon ($\mathrm{C_{org}}$) into two separate pools of inert C ($\mathrm{C_i}$) and decomposable C ($\mathrm{C_{dec}}$) of which only $\mathrm{C_{dec}}$ is the determining factor for soil fertility.

When SOM (or $\mathrm{C_{dec}}$) is being degraded by microorganisms it supplies nutrients to crops but SOM also has indirect effects on the soil by improving the chemical, biological and physical soil properties which amongst other things increases the nutrient availability through increasing the cation exchange capacity (Amelung et al., 2018; Körschens, 2010; Watson et al., 2002). The main factor determining the yield is the supplied N through decomposition of $\mathrm{C_{dec}}$

and not the improved soil characteristics (Körschens et al., 1998). The higher the clay content of the soil the higher the $\mathrm{C_i}$ and $\mathrm{C_{dec}}$ content because $\mathrm{C_{dec}}$ mineralization rate is slow. In sandy soils there is less $\mathrm{C_{dec}}$ because of the faster mineralization rate but the proportion of $\mathrm{C_{dec}}$ of the total $\mathrm{C_{org}}$ is higher because $\mathrm{C_i}$ is also low. While sandy soils do not even have > 0,4 % of $\mathrm{C_{dec}}$, loam and loess soils (Kleinhohenheim has a clayey loam soil) can reach an optimum $\mathrm{C_{dec}}$ content of maximum 0,6 % (Körschens et al., 1998).

SOM is a part of the earth's carbon cycle and therefore undergoes changes for example by being used and degraded as an energy source by microorganisms. The average turnover time for SOM on arable land is estimated to be 7 years (Amelung et al., 2018). When SOM is lost over time a decline in soil fertility would be the consequence. Not only the organic farming principles demand a sustainable management of SOM to ensure soil fertility (IFOAM, 2017) but also the German "Bundes-Bodenschutzgesetz" (cf. § 17 Sec. 2 BBodSchG) states that farmers should sustain the typical SOM content of their farmland for a sustainable and high productivity of the land. In reality, it is quite difficult to determine the typical SOM content of a specific location because not only do the soil characteristics influence the typical SOM content but also the agricultural land management (BLE, 2022). Furthermore, a measurement of the SOM content is very difficult and is typically done by measuring the $\mathrm{C_{org}}$ content of the soil and then multiplying by 1,724 (Körschens, 2010). Even the measurement of $\mathrm{C_{org}}$ is subject to spatial and temporal variability and has therefore an approximate error of >0,1 %. Because the annual changes of $\mathrm{C_{org}}$ content of the soil are less than 0,01 % even under extreme land management changes it is practically impossible to use $\mathrm{C_{org}}$ as an indicator for the total SOM content of the soil. That is why SOM budgets are the only valid method at the time to reliably estimate the subsistence of the soil with OM (Körschens, 2010).

1.3.2. Reproduction of soil organic matter

Long-term experiments are essential for figuring out important parameters which influence the SOM content because only long-term experiments can exclude the natural fluctuations of the SOM content (Körschens et al., 2013). The main parameter which influences the SOM content is OM. To impede soil fertility loss, the SOM content has to be replenished by adding fresh OM to the soil.

To maintain the current SOM content and to be able to calculate SOM budgets, knowledge about the OM materials and their ability to increase the SOM content has to be acquired. The

SOM reproduction capacity (SOM-RC) of the different OM materials can only be determined with long-term experiments because SOM content changes only marginally and over long time periods (Joschko et al., 2010). VDLUFA (2014) defined the SOM-RC for a lot of OM materials (which is stated as the unit "Humusäquivalente" = "SOM equivalent") based on long-term experiments conducted with several mineral and organic fertilizers on different soil types and under different crop rotations. According to this classification 1 t FM of straw results in 100 kg SOM-C, compost in 40-66 kg SOM-C, liquid BD ~ 6-12 kg SOM-C and manure in 40-56 kg SOM-C reproducing the SOM content in the soil. The Excel tool used in this research (LEL Schwäbisch Gmünd, 2006) was based on the VDLUFA method.

Straw is the most important organic fertilizer for SOM reproduction on arable land in Germany (Kehres and Reinhold, 2008) and also one of the main OM inputs for Kleinhohenheim at the moment. But the SOM-RC of straw is still a subject of debate and different long-term experiments show different results. Joschko et al. (2010) argued based on their modelling that the SOM-RC of straw could be higher than the values of VDLUFA. On the other hand, lower SOM-RC for straw in long-term experiments were found in Puch, Spröda and Methau (Körschens (2005) as cited in Joschko et al. (2010)).

It is important to note, that the SOM-RC of straw seems to be site-independent (Joschko et al., 2010). Therefore, the SOM-RC of straw is always the same but there are differences of the SOM content between sites even if they receive exactly the same amount of straw. This is due to the different SOM dynamics of the sites which are in an equilibrium between SOM reproduction through OM and degradation of SOM (Joschko et al., 2010). While the SOM reproduction stays the same when the same amount of straw is applied the degradation of SOM varies due to site-specific mineralization rates. In general, loam soils have higher SOM contents because of the lower biological activity which slows down degradation while sandy soils have lower SOM contents due to higher biological activity (Joschko et al., 2010).

Regardless of the "theoretical" SOM-RC of straw or other OM materials, there are long-term experiments directly measuring actual changes in SOM content when different OM materials are applied. The SOM content varies strongly in space and time which is why only long-term experiments can reliably determine SOM content changes (Körschens et al., 2013).

When there was no fertilization over 45 years the highest C losses occurred (Zimmer et al., 2005). The fallow treatment lacking the crop and root residues resulted in a SOM content decrease in only 10 years (Körschens et al., 2013). Only using green manure also led to high C losses. C losses could be reduced by fertilizing with straw but straw fertilization could only slow down the C loss but not completely prevent it. Only when straw was applied with mineral fertilizer or green manuring the C soil content stayed constant over the 45-year period (Zimmer et al., 2005). On the other hand, Herbst et al. (2016) found that only straw fertilization was enough to achieve constant C content in the soil over 46 years and straw fertilization with additional mineral fertilizer even increased the C content. Joschko et al. (2010) also found that the higher the mineral N fertilization (combined with straw) was, the better was the C accumulation in the soil. These different results might be due to the different experimental locations (and their soil types) which have different mineralization rates and therefore straw fertilization led to different results depending on the location (Joschko et al., 2010).

Kleinhohenheim as an OF does not import mineral fertilizers which would mean a low C accumulation through straw can be expected because straw is applied to the fields without mineral N fertilization. According to Zimmer et al. (2005) the only possibility for Kleinhohenheim to achieve steady C soil content would be the application of straw in combination with green manure.

Furthermore, incorporation of straw has additional benefits for the soil. Ocio et al. (1991) showed that soil microbial biomass increased after straw incorporation. Even one year later microbial biomass was still 20 % higher than on the fields receiving no straw. Powlson et al. (1987) showed that there were only slight but not significant increases in $\mathrm{C_{org}}$ after 18 years of annual straw incorporation and it was suggested that soil microbial biomass might be an indicator for increasing SOM contents. But Ocio et al. (1991) suggests that the microbial biomass is not only influenced by long-term substrate inputs but also highly influenced by short-term inputs making microbial biomass unsuitable as an indicator. The SOM increase might be overestimated (when using microbial biomass as an indicator) especially after a recent substrate input which increased the soil microbial biomass.

The only fertilizers which achieved a C soil content increase in many different studies were farmyard manure (FYM) and liquid manure (Herbst et al., 2016; Joschko et al., 2010; Zimmer et al., 2005). Körschens et al. (2013) found an average increase of 0,3 % SOM content when 10 t $\mathrm{ha^{-1}\ year^{-1}}$ FYM and mineral fertilizer was applied compared to the unfertilized variant. The more FYM was applied the higher the $\mathrm{C_{org}}$ difference to the fallow treatment (Körschens et al., 1998). This does not mean that organic fertilization with manure can be increased indefinitely but fertilizer should only be applied in the "right" amounts (which seemed to be 10 t $\mathrm{ha}^{-1}\ \mathrm{year}^{-1}$ according to Körschens et al. (2013)) to compensate the C losses and achieve optimal yields while reducing adverse effects on the environment (such as leaching) (Körschens et al., 1998). Similar results were found by Joschko et al. (2010) who also found FYM to increase the SOM content more than straw combined with mineral N fertilization. On one location FYM increased the $\mathrm{C_{org}}$ content and straw (with mineral N fertilization) just maintained the $\mathrm{C_{org}}$ content of the soil while on another location FYM only maintained the $\mathrm{C_{org}}$ content and straw (with little mineral N fertilization) led to a decrease of $\mathrm{C_{org}}$ content. This shows that despite variations between the locations FYM always increases (or maintains) the $\mathrm{C_{org}}$ content more than straw (Joschko et al., 2010). This was also confirmed by Körschens et al. (2013) who found that straw only has 60 % of the soil organic carbon (SOC) reproduction capacity of FYM but up to 74 % SOM-RC was found by Joschko et al. (2010).

Another important finding of Herbst et al. (2016) was that the yield of the cash crops influences the SOM content more than the SOM content influences the yield. More yield results in more OM such as by-products and root residues which increase SOM content. The easiest way to increase yields is with mineral fertilization (N, P and K) which is why it was shown that mineral fertilization increased SOM content (on soils with low SOM content) (Herbst et al., 2016). While Kleinhohenheim does not use mineral fertilizers these findings could also mean that the import of organic fertilizers (e.g. BD, compost) to Kleinhohenheim could not only increase the SOM content directly (because they consist of OM) but also increase the SOM content indirectly through producing higher yields.

On the other hand, Zimmer et al. (2005) found no increase of SOM content after mineral fertilization. The mineral fertilization resulted in the same or an even higher C loss than the unfertilized variant. So, the results remain inconclusive but the mineral fertilization could not be a solution for OA anyway.

It is important to keep in mind that SOM changes in long-term experiments are influenced by the previous SOM content before the experiment started. A high SOM content due to previous management strategies (high OM inputs) might decrease when the experiment is started with less OM inputs. The SOM content decreases until a new equilibrium between OM inputs and SOM content is reached (Körschens et al., 2013). So, the OM inputs are not the reason for the

SOM decrease but instead the SOM content settles on a lower equilibrium. This was the case in experiments in Methau and Spröda (Körschens et al., 2013). If the previous SOM content is not included in the assessment of long-term experiments, it is not possible to distinguish between a low initial SOM content which was increased or a sufficient initial SOM content which was only maintained throughout the experiment. Other factors influencing and lowering the SOM content equilibrium are changes in the environment and management practice changes such as deeper tilling (Körschens et al., 1998).

While Hodges (2003) claims that there are adequately with SOM supplied and therefore successful stockless OFs Ebertseder et al. (2010) are unsure of the actual influence of livestock on the SOM content. Because even though Ebertseder et al. (2010) found the soil type and altitude to have a much bigger influence on SOM contents there was also a small but significant difference between farming strategies shown. SOM contents of OFs with livestock were higher than SOM contents of stockless OFs. Hence, Kleinhohenheim as a stockless farm could have lower SOM contents and lower SOM budgets because it is missing organic fertilizers from livestock which was shown to have the highest SOM reproduction effect (Ebertseder et al., 2010).

1.3.3. Soil organic matter budgets

When conventional agriculture and OA have the same crop rotation conventional farming has better SOM budgets because of a higher N fertilization. A higher N fertilization results directly in higher SOM budgets because the higher the N fertilization the higher the yields and the by-products of the crops which reproduce SOM. Therefore, conventional farms often have more by-products than OFs and consequently higher SOM budgets (Breitschuh and Gernand, 2010; Brock et al., 2012).

Comparing an arable scenario without any inputs for organic and conventional farming organic farming had the higher (negative) SOM budget than conventional farming because there were more legumes in the crop rotation of OA. In another scenario with straw fertilization and catch crops included all SOM budgets increased (but were still negative) and were still higher for OA. The last scenario with animal manure as an input increased the SOM budgets (still negative but only slightly) for both OA and conventional agriculture but there was no difference between OA and conventional agriculture. Even though OA had higher budgets in the arable and straw fertilization scenario the SOM budgets were still more negative than in the animal manure scenario (Brock et al., 2012).

Flores-Sánchez et al. (2015) also found that SOM budgets of stockless farms could be increased by leaving the crop residues on the fields. But farms with livestock had higher SOM budgets because high feed imports resulted in high FYM amounts which could then be used or recycled the fields of the farm (Breitschuh and Gernand, 2010; Flores-Sánchez et al., 2015). OFs had on average less livestock than conventional farms (Breitschuh and Gernand, 2010) which might indicate that Kleinhohenheim could also struggle with negative SOM budgets because Kleinhohenheim did not use or import any animal manure.

On the other hand, Breitschuh and Gernand (2010) found slightly higher SOM budgets for OFs and explained this with the higher share of SOM reproducing crops in the crop rotation of OFs and OFs did not sell as much straw and left it on the fields. Even though OFs had less by-products and no sewage sludge or compost imports (compared to conventional farming) the crop rotation and retention of straw compensated this difference in SOM reproduction and even resulted in higher SOM budgets for OFs. The average SOM budget of all farms was + 277 kg SOM-C $\mathrm{ha}^{-1}\,\mathrm{year}^{-1}$ while the average SOM budget of OFs was + 296 kg SOM-C $\mathrm{ha}^{-1}\,\mathrm{year}^{-1}$.

1.4. Objective and hypotheses of this research

1.4.1. Nutrient farm-gate budgets of the current management

One objective of this research was to attain a better understanding of the current nutrient supply of the stockless arable organic research farm Kleinhohenheim. Hence, nutrient budgets were calculated for the arable crop rotation of Kleinhohenheim (KH1 to KH8). The researched part of Kleinhohenheim did not receive any external fertilizer, so the following hypotheses were tested for the farm-gate budgets:

- Kleinhohenheim (as an arable OF under stockless management without any external fertilizer inputs) has negative nutrient budgets for P and K while N budgets are positive because of the N input through BNF.
- The higher the BNF share the higher the N budgets and the lower the P and K budgets because more N fixating plants lead to more plant outputs (through higher yields) subsequently decreasing P and K budgets.

1.4.2. Nutrient field budgets of the current management

To get a more detailed assessment of the nutrient supply of individual fields of Kleinhohenheim further hypotheses were tested for nutrient field budgets:

- Some fields have positive field nutrient budgets because there was a nutrient input through clover grass silage (CGS) application.
- The average of all field budgets should be similar to the farm-gate budgets. Positive average N field budget (because of BNF) and negative average P and K budget (because CGS only shifts nutrients between the fields farm internally, but there is no external P or K input)

1.4.3. Nutrient farm-gate budgets with fertilizer input

For the nutrient farm-gate budget scenarios with fertilizer inputs the main objective was to see how theoretical fertilizer inputs influence the nutrient farm-gate budgets. On this basis it could be possible to find fertilizer solutions which can ensure a sustainable nutrient supply to Kleinhohenheim. This is why the following hypothesis was tested:

- Fertilizer inputs (compost, BD, struvite) compensate P and K budget deficits and even result in positive P and K budgets. The N budgets will also further increase with the fertilizer inputs.

1.4.4. Soil organic matter farm-gate and field budgets

The next objective was the assessment of the current SOM supply of Kleinhohenheim (KH1 to KH8). Because Kleinhohenheim uses only the straw of the crops as OM input to the soil and the previously mentioned long-term experiments showed that straw fertilization has a lower SOM-RC than FYM negative SOM budgets can be expected. On the other hand, according to VDLUFA (2014) straw has the highest SOM-RC which might result in positive SOM budgets. OFs with livestock or the application of manure always had higher budgets than arable farms which might indicate that Kleinhohenheim under stockless management could have negative SOM budgets (Breitschuh and Gernand, 2010; Brock et al., 2012). Therefore, SOM farm-gate and field budgets were calculated and the following hypotheses tested:

- Kleinhohenheim (as an arable OF under stockless management without any external OM inputs) has negative SOM farm-gate and field budgets.

2. Material and methods

2.1. The organic research farm Kleinhohenheim

The organic research farm Kleinhohenheim is located in the South East of Stuttgart in South Western Germany (48°44'16.7"N 9°12'02.7"E) in a temperate climate. The medium annual temperature of the last 6 years was 10.6°C (Kleinhohenheim) and the medium precipitation was 588,2mm (Agrarmeteorologie Baden-Württemberg, 2023) (Figure 1).

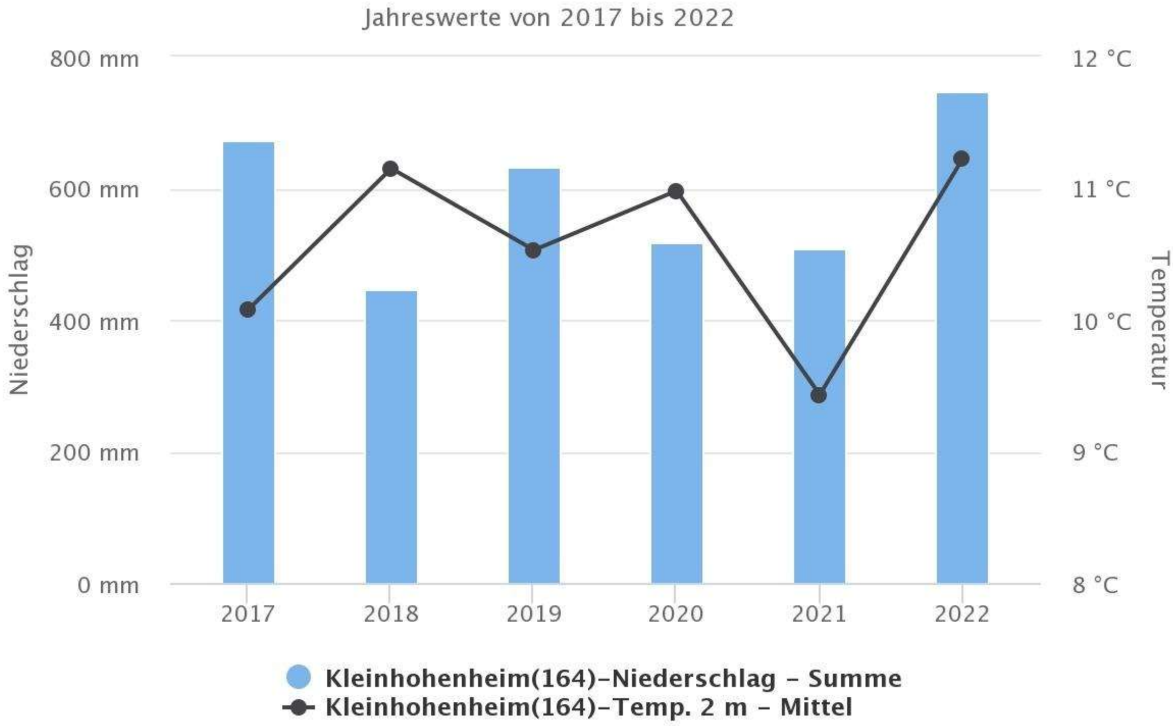


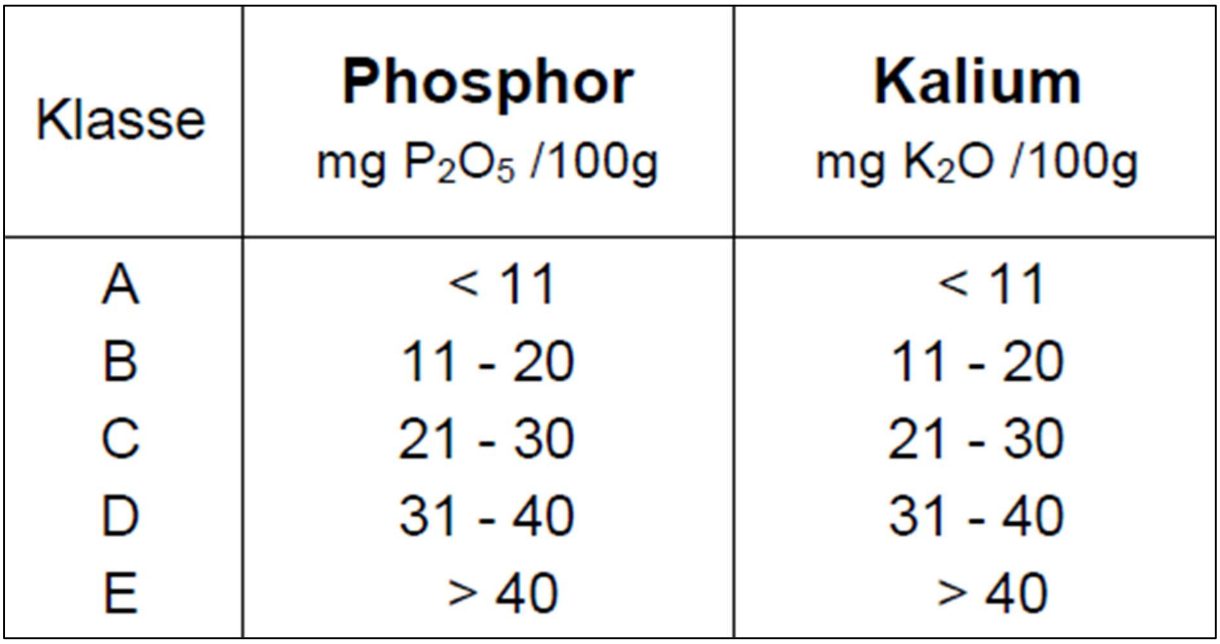
Figure 1: The temperature and precipitation of the last 6 years at Kleinhohenheim (medium temperature was 10.6°C and medium precipitation was 588,2mm). Source: Agrarmeteorologie Baden-Württemberg (2023).

Kleinhohenheim comprises an area of 65 ha, with 35 ha of arable fields, 23 ha of grasslands and 7 ha of roads, buildings and field margins. All fields of Kleinhohenheim are under long-term stockless management since 2010 (Simon Schäfer pers. comm.) but nutrient budgets were only calculated for specific fields (labelled as KH1 to KH8). These fields did not receive any external fertilizers since at least 2010 and comprise a total area of 22,13 ha. The location and exact size of each field is shown in Figure 2. Soil analyses of each field were conducted in 2016 and 2021 for the nutrients P and K which classify the nutrient contents into content classes (Table 1 and Table 2). Furthermore, soil analyses were also conducted for SOM contents (Table 3). The soil analyses were compared to the nutrient and SOM budget results in chapter 0 and

4.7 to contextualize the nutrient and SOM budget results and to see if the nutrient and SOM budget results are reflected by the soil nutrient and SOM contents. Other fields such as TS1 to TS7 were fertilized with FYM from the Meiereihof, another research farm of the university. KH1 to KH8 and the years 2016 to 2022 were selected for the budget calculations to see the effect of an unidirectional flow of nutrients and OM away from the farm (stockless management without external inputs) on the soil. In the following the researched arable crop rotation (comprising fields KH1 to KH8) of Kleinhohenheim is referred to as "Kleinhohenheim".

Figure 2: Overview of the organic research farm Kleinhohenheim and its fields. The labelling of KH 1 to KH 8 was enhanced because nutrient budgets were calculated for these fields. Source: Simon Schäfer, modified, Appendix IV

Table 1: "Content classes" for arable soils for P and K from A to E. A = very low, B = low, C = optimal, D = high, E = very high. Source: LTZ (2023a)



Klasse	**Phosphor** mg P_2O_5 /100g	**Kalium** mg K_2O /100g
A	< 11	< 11
B	11 - 20	11 - 20
C	21 - 30	21 - 30
D	31 - 40	31 - 40
E	> 40	> 40

Table 2: Soil nutrient analyses from fields KH1 to KH8 carried out by LTZ Augustenberg in March 2021 (Appendix I) and March 2016 (Appendix III). Samples were originally taken from south and north parts of the fields but averaged for each field. CC = content classes; t'L = "leicht toniger Lehm" = clayey loam. Phosphorus and Potassium contents were measured as P_2O_5 and K_2O. *only first sample was noted because second sample had improbable high nutrient contents.

		March 2021				**March 2016**			
Sample from	Soil type	Phosphorus [mg / 100 g]	CC	Potassium [mg / 100 g]	CC	Phosphorus [mg / 100 g]	CC	Potassium [mg / 100 g]	CC
KH1	t'L	8	B	18,5	B	11*	C*	19*	B*
KH2	t'L	7,5	B	16,5	B	9,15	B-C	18,5	C
KH3	t'L	11,5	C	13	B	15,5	C	15	B
KH4	t'L	13	C	13	B	14	C	15,5	B
KH5	t'L	8	B	14	B	9	C	15	B
KH6	t'L	9	B	6	A	12	C	9,1	A
KH7	t'L	10,5	B-C	15,5	B	12	C	15	B
KH8	t'L	7,5	B	10	A-B	9	B-C	9,55	B
average		9,375	B	13,313	B	11,46	C	14,58	B

Table 3: Soil organic matter analyses from fields KH1 to KH8 carried out by LTZ Augustenberg in March 2021 (Appendix I) and March 2016 (Appendix III). Samples were originally taken from south and north parts of the fields but averaged for each field. t'L = "leicht toniger Lehm" = clayey loam.

		March 2021	**March 2016**
Sample from	Soil type	SOM %	SOM %
KH1	t'L	1,8	2,35
KH2	t'L	1,65	2,1
KH3	t'L	1,9	2,19
KH4	t'L	2,65	2,64
KH5	t'L	1,85	2,26
KH6	t'L	1,6	2,34
KH7	t'L	2,55	2,64
KH8	t'L	2,35	2,72
average	t'L	2,04	2,41

2.2. Data management

The necessary data for the nutrient and SOM budget calculations were obtained from Simon Schäfer (manager of the research farm Kleinhohenheim) and the field record data base which was located at the Meiereihof, another research farm of the university. Simon Schäfer provided data for the years 2020, 2021 and 2022. The data base contained data from the year 2016 to 2019. This way, nutrient and SOM budgets could be calculated for a whole 7-year crop rotation.

The provided documents and the data base were screened for inputs (seeds, fertilizers, BNF, etc.) and outputs (plant products, straw, etc.) from the year 2016 to 2022 for the fields KH1 to KH8. Furthermore, information about management practices on the different fields and what inputs or outputs a field received was gathered. Sometimes the data from the different sources (Simon Schäfer, data base with different Excel files) did not coincide. Simon Schäfer (pers. comm.) said that his documents from 2020-2022 are more reliable than the data from the data base, therefore his data was used for the budget calculations. Two documents were collected from the data base. One was listing the exact treatments ("Verfahren") of each field and the other was an overview over the last years yields ("Übersicht"). When the data from these two documents contradicted themselves the data from the "overview" document was used. When no data was available from Simon Schäfer or the "overview" document the data from the "treatment" document was noted. The data from the data base was checked for plausibility and when neither Simon Schäfer nor the data base could provide sufficient reliable data, it was estimated from literature (e.g. for nutrient contents of seed imports or yield exports) (Table 4).

To simplify the calculation and because of a lack of reliable data, field experiments which took place on KH1 to KH8 in the 2016 to 2022 time period and the related in- and outputs were not considered for the budget calculations. Instead, the fields where the experiments took place were included in the budget calculations only with the crop noted in the crop rotation plan. Furthermore, there was no information about the use of the CG cuttings of the period 2016 to 2019. It was assumed that all CG cuttings were used to make silage, therefore the nutrients and SOM of the CG stayed on the farm. It was also noticed that the field sizes of KH1 to KH8 varied from year to year when looking at the ha information of the yields. So, in some years the area of the arable crop rotation was in total larger or smaller than 22,13 ha (Figure 2). Instead of dividing the nutrient and SOM budgets per year with the accurate total field sizes (which varied from year to year), they were always divided by 22,13 ha to get the budgets per ha per year.

After the screening the relevant data was listed in a separate Excel file (Appendix IV, Excel file "Overview_Data_Budgets_organized.xlsx") to bundle every important information in one central place. If any data was incomplete or missing, it was either extrapolated on the basis of existing data (e.g. average of multiple years) or estimated from literature data (Table 1). The source of the data (either documents from Simon Schäfer, the data base or estimation from literature) was also noted in the Excel file. The data required for the budget calculations could then be linked from that data Excel file to all the different budget Excel files. This way it is ensured, that if the data set changes, the budgets change as well.

Table 4: Estimated data for nutrient and SOM budget calculations based on literature sources or assumptions made from existing data. Nutrient contents (N, P, K) given in [kg / 100kg fresh matter (FM)]. *Broad bean was sometimes ploughed before grain ripeness so there was no yield. Still, when broad bean grew it fixated N. To be able to estimate the BNF of ploughed broad bean the yields of broad bean from 2022, 2021, 2018 and 2016 were averaged and half of this average yield was assumed for calculating the BNF of ploughed broad bean.

Missing information	Obtained data	Values	Source
Buckwheat	Contents of N, P, K	N: 1,66 | P: 0,31 | K: 0,43	Köhler and Kolbe (2007)
Buckwheat	Grain/straw ratio	1:2,3	LLG Sachsen-Anhalt (2019)
Buckwheat	SOM diminishing effect	-280 kg C ha^{-1} year^{-1}	Kolbe and Köhler (2008) grouped into the category of: „Getreide: einschließl. Öl- u. Faserpflanzen, So.-Blume"
Amount of rye straw exported in 2020 & 2021 for nutrient budgets	Grain/straw ratio	1:0,9	Excel-program "Humusbilanz Vers. 1.3" from LEL Schwäbisch Gmünd (2006)
Broad bean when getting ploughed before grain ripeness*	Average yield	1,7 t ha^{-1}	Broad bean yield of 2022, 2021, 2018 and 2016 averaged and halved*
Lentil seeds	Contents of N, P, K	N: 3,58 | P: 0,479 | K: 1,16	LfULG Sachsen (2019) and LTZ (2023b)
Lentil yield	Contents of N, P, K	N: 3,9 | P: 0,39 | K: 0,76	Köhler and Kolbe (2007)

Lentils	Seeding rate	112,5 kg ha^{-1}	LTZ (2022)
Lentils	Average yield	1 $\mathrm{t\ ha}^{-1}$	LTZ (2022)
CGS	Contents of N, P, K	N: 1,985 | P: 0,196 | K: 1,937	Zikeli et al. (2022)
CG undersown in rye	Average yield	9,44 t FM ha^{-1}	LfL (2018)
CGS	SOM reproduction [kg SOM-C t^{-1}]	115 kg C t^{-1} DM	Kolbe (2013)
Struvite	Contents of N, P, K	N: 5,4 | P: 11,6 | K: 0,03	Rittl et al. (2019)
Struvite	Fertilization recommendation	330 kg ha^{-1}	Weiß (2022)
Carbonated lime	Contents of N, P, K	N: 0,19 | P: 0,35 | K: 0,06	Möller and Schultheiß (2014)
BD (liquid) from plant material	Fertilization recommendation	12 $\mathrm{t\ ha}^{-1}\ \mathrm{year}^{-1}$ which is equal to 60 kg N $\mathrm{ha}^{-1}\ \mathrm{year}^{-1}$	(DüV, 2017; Wendland and Lichti, 2012) N ha^{-1} estimated and adjusted to a lower level
BD (liquid) from plant material	Contents of N, P, K	N: 0,55 | P: 0,1 | K: 0,44	Möller and Schultheiß (2014)
Compost from biowaste	Contents of N, P, K	N: 0,94 | P: 0,2 | K: 0,63	Möller and Schultheiß (2014)
Compost from biowaste	Fertilization recommendation	60 kg N $\mathrm{ha}^{-1}\ \mathrm{year}^{-1}$ which means 6,38 $\mathrm{t\ ha}^{-1}\ \mathrm{year}^{-1}$	(DüV, 2017) and N ha^{-1} estimation like BD

Further calculations with some data taken from the literature (Table 4) were required to get the needed estimated value. In the following the most important calculations are listed.

The estimation for the average yield of CG undersown in rye was made with the help of a document from the LfL (2018). This document showed a graph with the average yields of rye and CG when rye was grown with undersown CG in the first and in the second year of cultivation. The average yield of CG undersown in rye in the first year of cultivation was approximately 3,9 t dry matter ha^{-1}. With a dry mass of 33 % (according to Simon Schäfer) the fresh matter of this CG must have been 11,8 t fresh matter (FM) ha^{-1}. It was assumed that Kleinhohenheim as an organic farm yields 20 % less than conventional agriculture which the data from the LfL (2018) might suggest (Seufert et al., 2012). Therefore, the final estimation for the average yield of CG undersown in rye was 9,44 t FM ha^{-1} (11,8 t FM ha^{-1} * 0,8 = 9,44 t FM ha^{-1}).

The SOM-RC of CGS had to be estimated as well. The fertilization with CGS is a relatively new concept which is why there is little data about the SOM-RC of CGS. Kolbe (2013) mentioned this problem for silage corn and estimated that the SOM-RC of silage corn could be classified between liquid BD and sewage sludge. The variation of the SOM-RC of liquid BD ranges from ~110 kg C t^{-1} DM to ~150 kg C t^{-1} and the SOM-RC of sewage sludge ranges from ~80 kg C t^{-1} to ~115 kg C t^{-1}. The median from this range of values is 115 kg C t^{-1} which was used as the estimated value for the budget calculations.

BD nutrient contents were already given in the nutrient budget Excel program. The nutrient content data was probably sourced from Möller and Schultheiß (2014) because the values coincide. The fertilization amount was chosen from Wendland and Lichti (2012) (120 kg N ha^{-1} year^{-1}) because it is well within the regulations of a maximum of 170 kg N ha^{-1} year^{-1} of § 6 Sec. 4 DüV. For BD with a N content of 0,55 % Kleinhohenheim would have to apply 21.818 kg (= 21,82 t = 21,82 m^3) per ha per year to achieve a fertilization of 120 kg N ha^{-1} year^{-1} (0,55 % N = 0,55 kg N per 100kg digestate and multiplication with factor ~ 218,18 to get 120 kg N per 21.818 kg digestate). Therefore, the farm-gate budgets needed a total BD input of ~ 482,88 t (21,82 t * 22,13 ha) per year to fertilize all fields. The fertilization recommendation from Wendland and Lichti (2012) was for whole-plant winter cereal silage which is why the farm-gate budgets with an input of ~ 482,88 t BD per year were expected to be sufficient to increase the nutrient budgets. After calculating the first budgets with this estimated BD input all nutrient budgets were highly positive and it was decided to half the estimated fertilization amount (~ 482,88 t/2 = 241,44 t) because it was enough to alleviate nutrient deficits (see chapter 3.3) and to minimize the risk of an oversupply of nutrients which would have detrimental effects on the environment.

The compost fertilization recommendation was chosen to be the same as the BD fertilization recommendation (60 kg N ha^{-1} year^{-1}). As already explained above, the 60 kg N ha^{-1} year^{-1}

estimation is well within the German regulations for fertilization of 170 kg N ha^{-1} year^{-1} (cf. § 3 Sec. 6 DüV) and within the recommendations of the German "Bioabfallverordnung" (cf. § 6 Sec. 1 BioAbfV) of 20 t DM ha^{-1}. 20 t DM ha^{-1} would translate to ~30,8 t FM ha^{-1} (20 t DM / 65 %DM (Buchholtz et al., 2019) * 100) which could then be applied over a three year period. So, it would be legal to apply ~10 t FM compost per ha per year. To achieve a compost fertilization of 60 kg N ha^{-1} year^{-1} with a compost nutrient content of 0,94 % N in FM (=9,4 kg N t^{-1}) an application of 6,38 t FM ha^{-1} year^{-1} (60 kg N ha^{-1} year^{-1} / 9,4 kg N t^{-1}) of compost would be needed. For the whole farm this would mean 141,2 t FM compost per year (6,38 t FM ha^{-1} * 22,13 ha). The value of 6,38 t FM ha^{-1} year^{-1} is under the threshold value of the German regulation of ~ 10 t FM ha^{-1} year^{-1}.

There were a few possible fertilization recommendations for struvite taken from field experiments. Rittl et al. (2019) used 345 kg of struvite per ha (which equals to 40 kg P ha^{-1}) while other experiments such as from Weiß (2022) used 330 kg of struvite per ha and another experiment from Weiß (2023) used 217 kg struvite per ha. In Germany there are regulations for fertilizers, in the case of P fertilizer (cf. § 3 Sec. 6 DüV) only the expected calculated P export can be compensated by fertilizer if the soil already contains more than 20 mg $\mathrm{P_2O_5}$/100g (=8,7 mg P/100g) soil after the CAL test or 25 mg $\mathrm{P_2O_5}$/100g (=11 mg P/100g) soil after the DL test. Because Kleinhohenheim did not reach these limits (Table 2), fertilization would be possible without these limitations. That's why a high fertilization amount from the literature was assumed as a possible P fertilization strategy. To alleviate the low P levels of Kleinhohenheim the median amount (330 kg ha^{-1}) of struvite fertilization was used in the budget calculations.

2.3. Budget calculations

The nutrient budgets were calculated with the Excel tool from the RELACS (Replacement of Contentious Inputs in Organic Farming Systems) project (Organic Farm Knowledge, 2023) because this tool was suitable for OA. This tool was available in German and English, thus the English version was used. Both the farm-gate and field budgets were calculated with this tool. To be able to use this tool for the field-budget calculations only one field was listed per year.

SOM budgets were calculated with version 1.3 of an Excel tool from the "Landesanstalt für Entwicklung der Landwirtschaft und der ländlichen Räume (LEL) Schwäbisch Gmünd" (LEL

Schwäbisch Gmünd, 2006). By following the instructions of the program and entering the data in the suitable Excel cells, this tool could calculate SOM farm-gate budgets. To calculate SOM field budgets some Excel cells were used differently than originally intended (e.g. the crop rotation cells (cell C11 to C17) represented the years from 2016-2022 from top to bottom and the "total arable land" cell (cell W249) represented only the area of the calculated field). The SOM field budget result was therefore the amount of kg SOM-C per ha, but this result had to be further divided by seven because the budget was calculated for a 7-year crop rotation.

The graphics of the results of the budgets were made with a self-made Excel file which was linked to the results in the budget Excel files (Appendix IV, Excel file "Graphics_of_results.xlsx").

2.3.1. Nutrient farm-gate budget calculations

As the name suggests nutrient farm-gate budgets only monitor the "gate" of the farm and what enters and leaves the farm. Then, the farm-gate budgets calculate the difference between the inputs and outputs of the farm (KH1 to KH8) (Öborn et al., 2003) which can be represented by formula (1):

$$\mathrm{Nut}_{\mathrm{Budget}} = \mathrm{Nut}_{\mathrm{Inputs}} - \mathrm{Nut}_{\mathrm{Outputs}} \tag{1}$$

Inputs to Kleinhohenheim included seeds, BNF and sometimes lime and outputs included all plant products of the farm. Furthermore, outputs included sometimes rye straw (2020 and 2021) and CG cuttings (2021 and 2022). All inputs and outputs of the farm were noted in the budget Excel program and subtracted from each other by the program. Due to the stockless management of Kleinhohenheim with just a few inputs the calculated budgets in this research included overall fewer inputs and outputs compared to other OFs (Figure 3). As shown in Figure 3 there were no inputs or outputs intended for or originating from animals and no other external fertilizers as inputs (crossed out). Internal farm nutrient flows are faded out in Figure 3 because they are irrelevant for the farm-gate budget calculations.

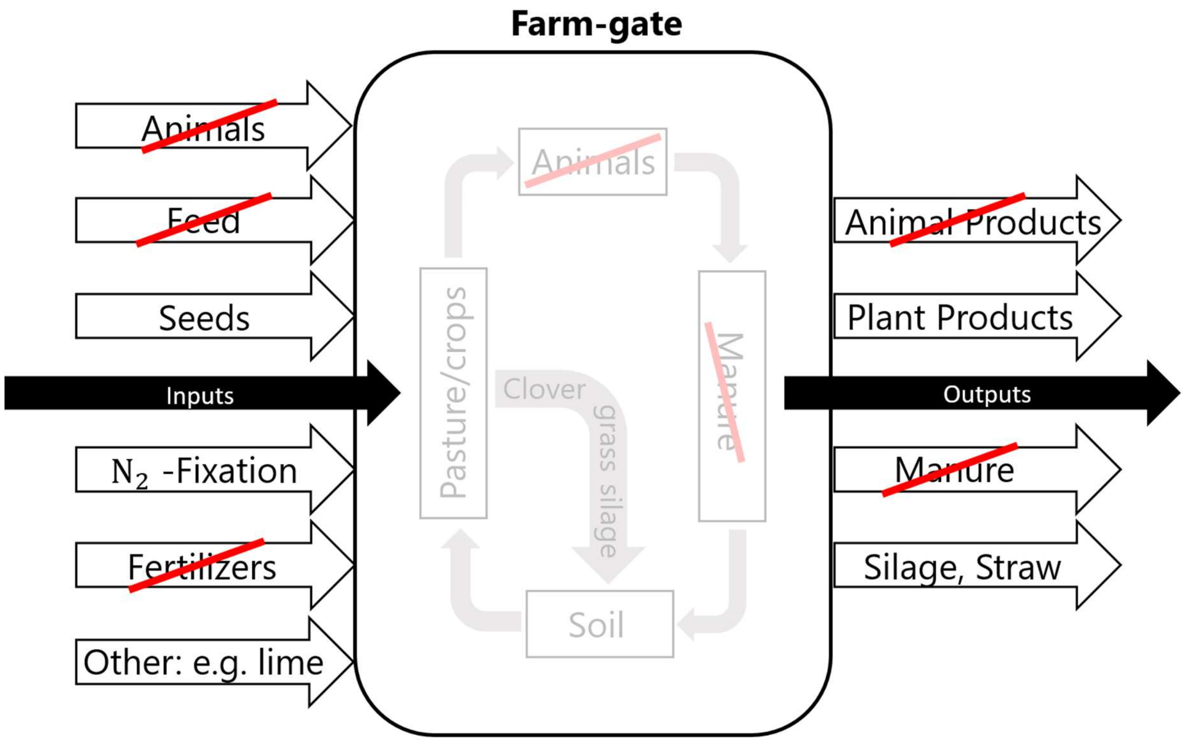


Figure 3: Schematic overview of nutrient farm-gate budget calculations. Inputs and outputs which were not relevant for this research are crossed out. Internal farm nutrient flows are faded out. Scheme adapted from Gourley et al. (2007) and Organic Farm Knowledge (2023).

2.3.2. Nutrient field budget calculations

Nutrient field budgets were calculated with the same formula (1) but instead of doing this calculation for the whole farm (KH1 to KH8) only one field was considered for the calculation. In addition to inputs such as seeds, BNF and lime field budgets also included CGS which is an internal farm nutrient flow between fields (Figure 4). The green arrows in Figure 4 show the possibilities of nutrient cycling for OFs. The CG (or CGS) or manure could be applied to other fields. Because Kleinhohenheim is a stockless OF manure is crossed out as a fertilizer and only CGS remains as a field fertilizer (Figure 4). Field outputs were the same as farm-gate outputs (plant products including sometimes straw and CG).

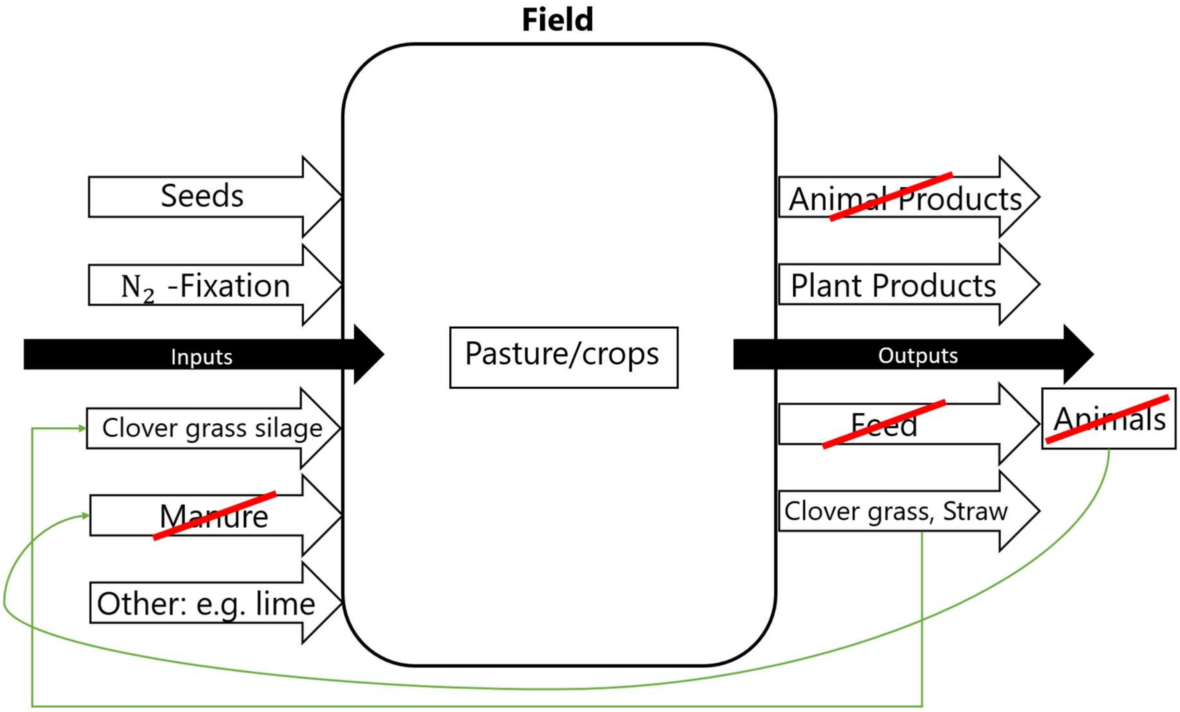


Figure 4: Schematic overview of nutrient field budget calculations. Animal associated inputs and outputs were not used or produced by Kleinhohenheim and are therefore crossed out. Scheme adapted from Gourley et al. (2007) and Organic Farm Knowledge (2023).

2.3.3. Nutrient farm-gate budget calculations with fertilizer input

The previously explained budget calculations were performed with data from the years 2016 to 2022 of the current management of Kleinhohenheim. Nutrient budget deficits were expected for P and K because Kleinhohenheim did not import any external fertilizer. Finding possible future fertilization strategies for Kleinhohenheim is one of the objectives of this research. Therefore, nutrient farm-gate budgets (including the data of the current management of Kleinhohenheim) were calculated with three different fertilizers as nutrient imports each year to see the effect of the fertilizers on the nutrient budgets. So, these fertilizer budget scenarios could also be described by formula (1) but additionally nutrient inputs included fertilizers (previously crossed out "Fertilizers" input in Figure 3 was now included). Outputs remained the same (only plant outputs) because even though the yield could have been higher due to the higher nutrient inputs through the fertilizers, yields were not adapted. The estimated data used for the fertilization scenarios is listed in Table 4 in Chapter 2.2.

2.3.4. Soil organic matter farm-gate and field budget calculations

SOM (farm-gate and field) budgets were calculated on the basis of the SOM effect of crops or OM which can either be a SOM loss or a SOM reproduction. This can be represented by formula (2).

$$\mathrm{SOM}_{\mathrm{Budget}} = \mathrm{SOM\ reproduction}_{\mathrm{crops}} - \mathrm{SOM\ loss}_{\mathrm{crops}} + \mathrm{SOM\ reproduction}_{\mathrm{OM}} \tag{2}$$

The SOM loss through crops was calculated in step 1 of the program. For some crops (e.g. clover grass and broad bean) the SOM reproduction effect of crops was also calculated in step 1. For most crops the SOM reproduction effect was calculated in step 2a by calculating the amount of by-products produced by the crop. Organic fertilizers which were imported to the farm or fields have a SOM reproduction effect and were calculated in step 2b. These factors were added up by the program to result in the final SOM budget. A schematic overview of formula (2) is shown in Figure 5.

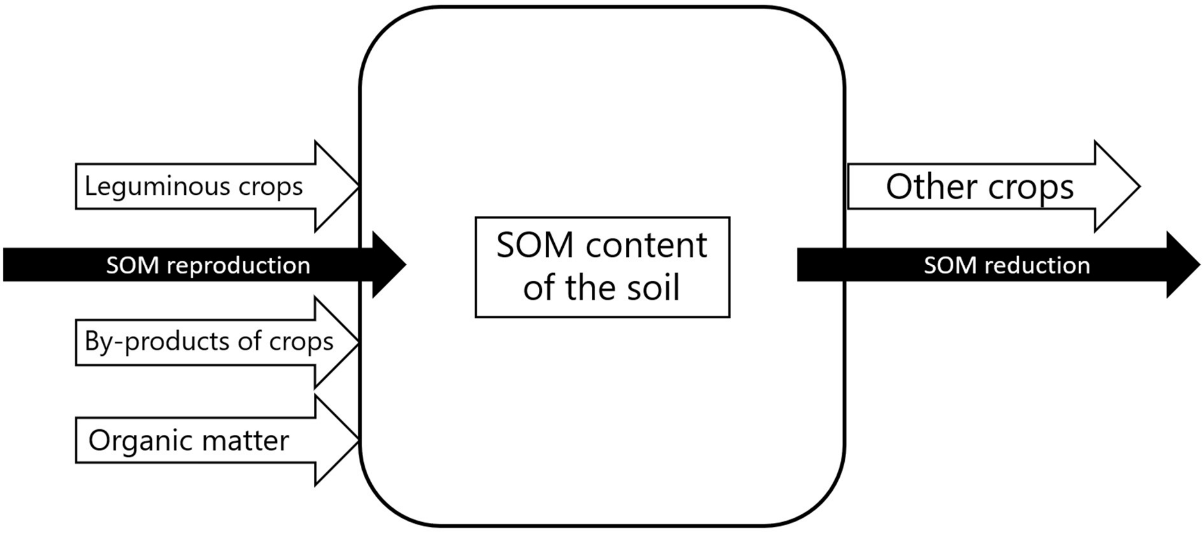


Figure 5: Schematic overview of SOM farm-gate and field budget calculations. "Organic matter" inputs could theoretically come from animals but Kleinhohenheim did not use any inputs from animals. Source: own figure

It is important to note, that the SOM farm-gate budgets were calculated without CGS as OM input in step 2b (also excluded in the nutrient farm-gate budgets) because it was assumed that the cuttings of CG were left on the field (in step 1) and therefore already contributed to the SOM reproduction (Werner Schmid, LEL Schwäbisch Gmünd, pers. comm.). If CGS would have been included as an OM input (in Step 2b) the SOM reproduction would have been calculated twice. In the SOM field budgets the CGS was included (as in the nutrient field budgets) because the silage did not originate from the same field on which it was applied as fertilizer.

2.4. Number of calculated budgets and Excel files

For every nutrient and SOM budget, farm-gate and field budget calculations were performed, which adds up to four types of budgets (Figure 6). Farm-gate budgets included all fields (KH1 to KH8) and were calculated for every year (2016-2022) which results in seven budgets. The budgets were calculated per calendar year, so it was assumed that sowing, fertilization and harvesting all happened in one calendar year, even though this might not be the case for some (winter) crops. Field budgets included all years (2016-2022) which means the whole 7-year crop rotation and were calculated for each field (KH1 to KH8) which resulted in eight budgets. Therefore, 30 budgets of the current management of Kleinhohenheim were assessed.

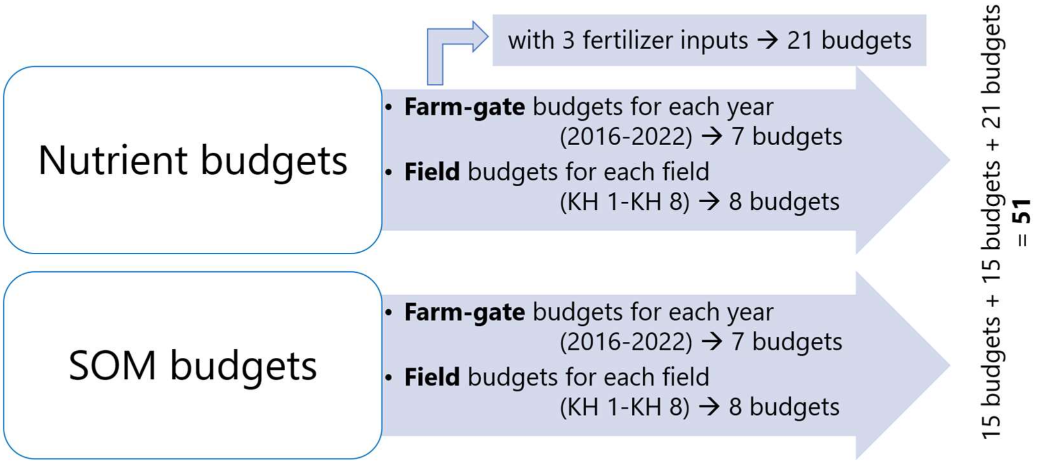


Figure 6: Overview of all budget calculations. Source: own figure

To investigate which fertilizers could compensate the (expected) nutrient deficiencies of the current management of Kleinhohenheim, each nutrient farm-gate budget (2016-2022) was calculated with three different fertilizers. In total, 21 (seven years * three fertilizers) fertilization scenario budgets were calculated.

For the calculation of each SOM budget one Excel file was needed (in total 15 Excel files as shown in Figure 6). But the theoretical number of nutrient budgets needed (Figure 6) did not match the number of Excel files. Due to the structure of the nutrient budget Excel program, budgets for three years were calculated at once. Hence, for a 7-year crop rotation the nutrient farm-gate budgets were grouped into three Excel files (2016, 2017-2019 and 2020-2022) instead of seven and the nutrient field budgets were split into three Excel files per field, which led to a total number of 24 budgets (three time periods (2016, 2017-2019 and 2020-2022) * eight fields) instead of eight. An overview of all budget Excel files is shown in the data Excel file (Appendix IV, Excel file “Overview_Data_Budgets_organized.xlsx”) in the sheet “list of budgets”.

3. Results

3.1. Nutrient farm-gate budgets of the current management

The farm-gate budgets were calculated for the whole farm (KH1 to KH8) in one calendar year. Comparing the budgets of the different years for one nutrient showed the yearly variation of the quantity of in- and outputs. The N farm-gate budgets fluctuated between the different years, depending on the crop rotation and the yield of the N fixing plants. The more N fixing crops grew on the farm in a year and the better their yield was, the higher the N input through BNF and therefore the N budget. In the years 2016, 2019 and 2020 there was less CG harvested than in 2017, 2018, 2021 and 2022 which is why the N budgets for the former years were negative and for the latter years were positive. It could also be observed that the 7-year average was slightly positive (+10 kg N ha^{-1} year^{-1}) which indicated that this crop rotation produces a surplus of N. This surplus is necessary to supply the crops with enough N but the surplus should not be higher than necessary because an oversupply of N would lead to lower N use efficiency and N leaching.

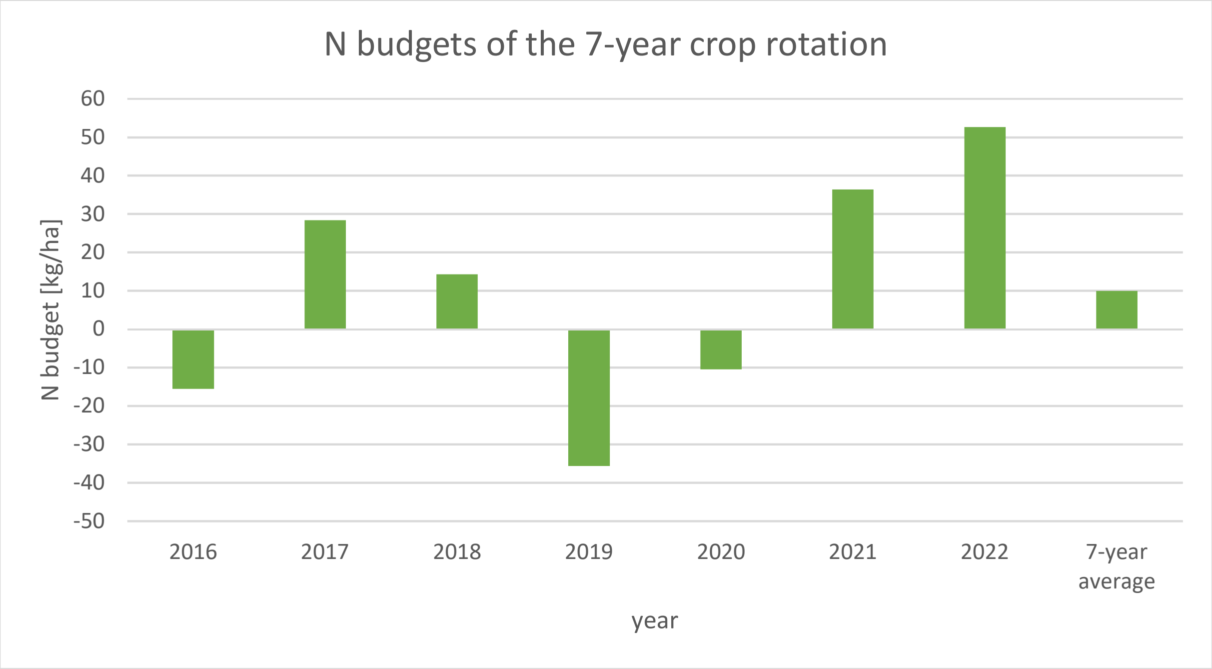


Figure 7: The N budget [kg ha^{-1}] of every year (2016-2022) and the 7-year average.

The P farm-gate budgets showed a very different picture. Almost every year the P budget was negative because there were no external inputs which could replenish the P lost through the crop exports. The only year with a marginal positive P budget was 2020 which could be explained by the high carbolime input ("Carbonated lime" as noted in Table 4) which contains some P. The 7-year average with -9 kg P ha^{-1} highlighted the P depletion of the soil in the long run.

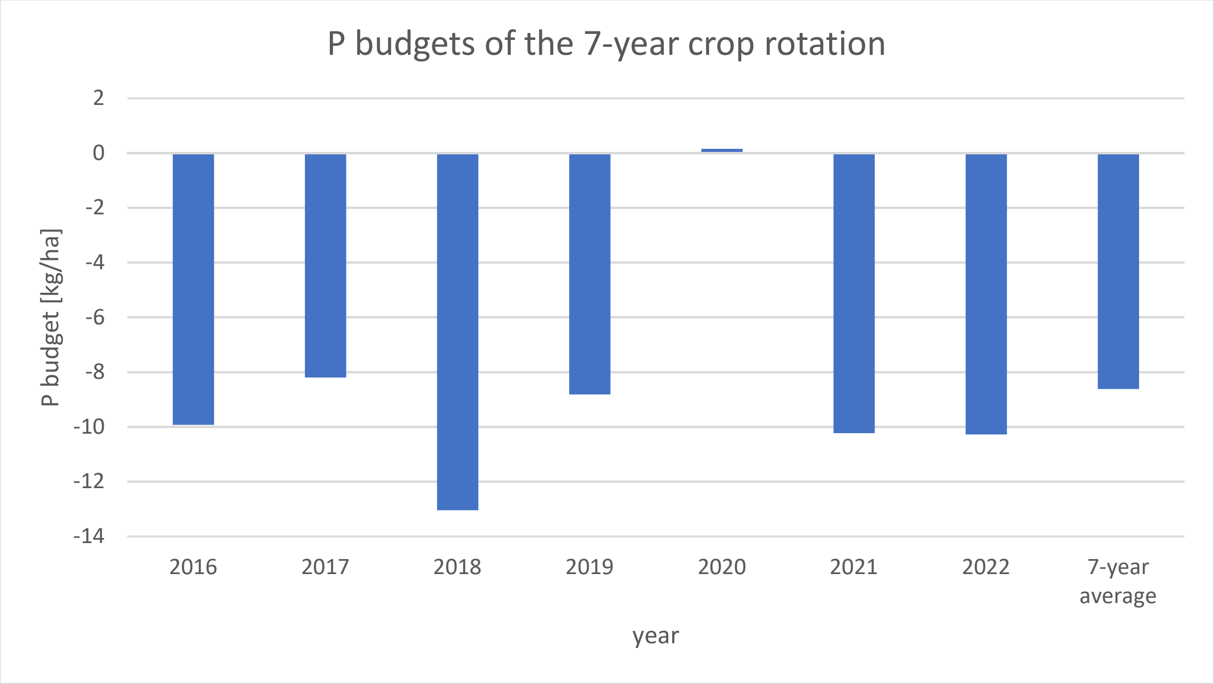


Figure 8: The P budget [kg ha^{-1}] of every year (2016-2022) and the 7-year average.

Upon reviewing the K budget results a similar pattern compared to the N budget results appeared: The K budgets fluctuated from year to year because of the liming. In 2018, 2019 and 2020 liming resulted in very high K budgets (the highest was +323 kg K ha^{-1} in 2020) while the other years had negative K budgets (most negative in 2021 with -46 kg K ha^{-1}) (Figure 9). Because of the high positive K budgets in 2018 to 2020 even the 7-year average was positive with +71 kg K ha^{-1}.

This was a rather surprising result because the budget calculations included no external inputs with high K contents. The reason for these high K budgets was found in the carbolime inputs which were included in the calculations as the program's default "Carbo lime". "Carbo lime" had 18 % K noted in its nutrient contents resulting in the high K budgets.

The literature showed other nutrient contents for carbolime which was why K budgets were calculated again with data from Möller and Schultheiß (2014) (Table 4). The "new" carbolime input (including 0,06 % K) was noted in the program as "Carbonated lime". All farm-gate and field budgets presented in chapter 3 were calculated with this input (except the K farm-gate budget in Figure 9 which was also calculated with the program's default "Carbo lime"). K farm-gate budgets were calculated with both carbolime inputs to show what effect the two different inputs have on the K budget results. The calculations with "Carbonated lime" resulted in negative K budgets for every year because K input from the "Carbonated lime" was much smaller than from "Carbo lime" (0,06 % compared to 18 %) and could not compensate the exported K. The most negative K budget was in the year 2021 with -46 kg K ha^{-1} and the 7-year average was also negative (-28 kg K ha^{-1}). These budget calculations with the more realistic carbolime nutrient contents ("Carbonated lime") from Möller and Schultheiß (2014) showed that there was a constant mining of K from the soils which is unsustainable because soil fertility is diminished in the long-term.

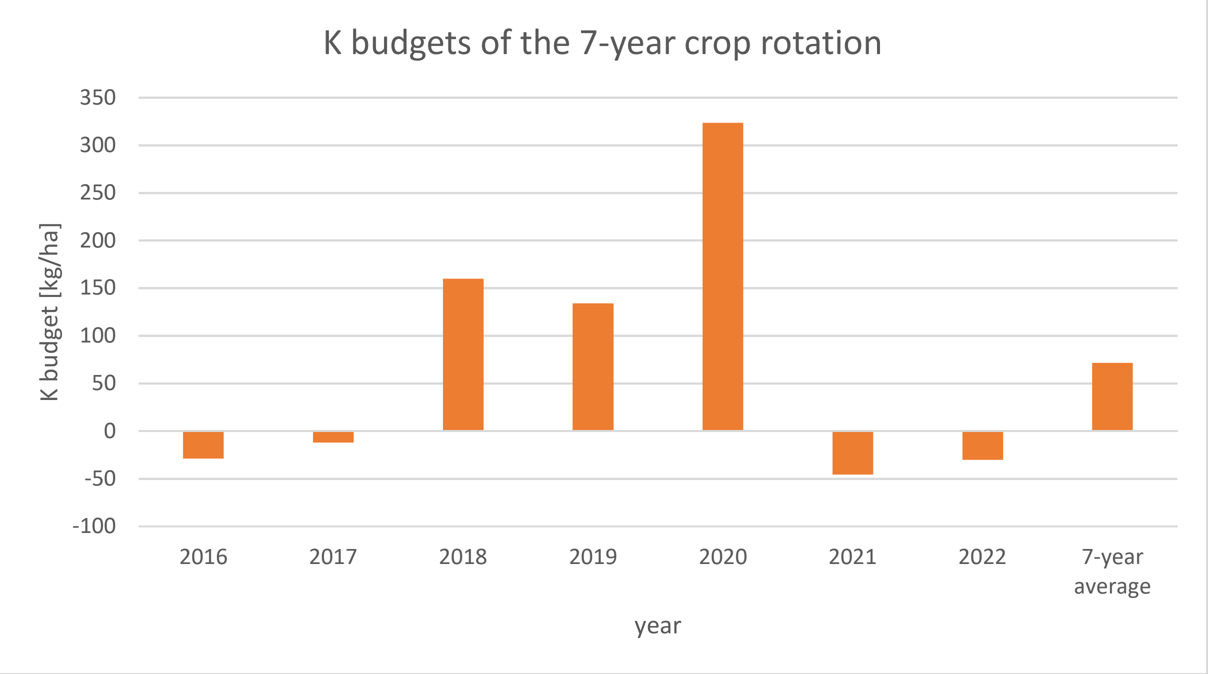


Figure 9: The K budget [kg ha^{-1}] of every year (2016-2022) and the 7-year average calculated with the input "Carbo Lime" which contains a high K nutrient content (18 %).

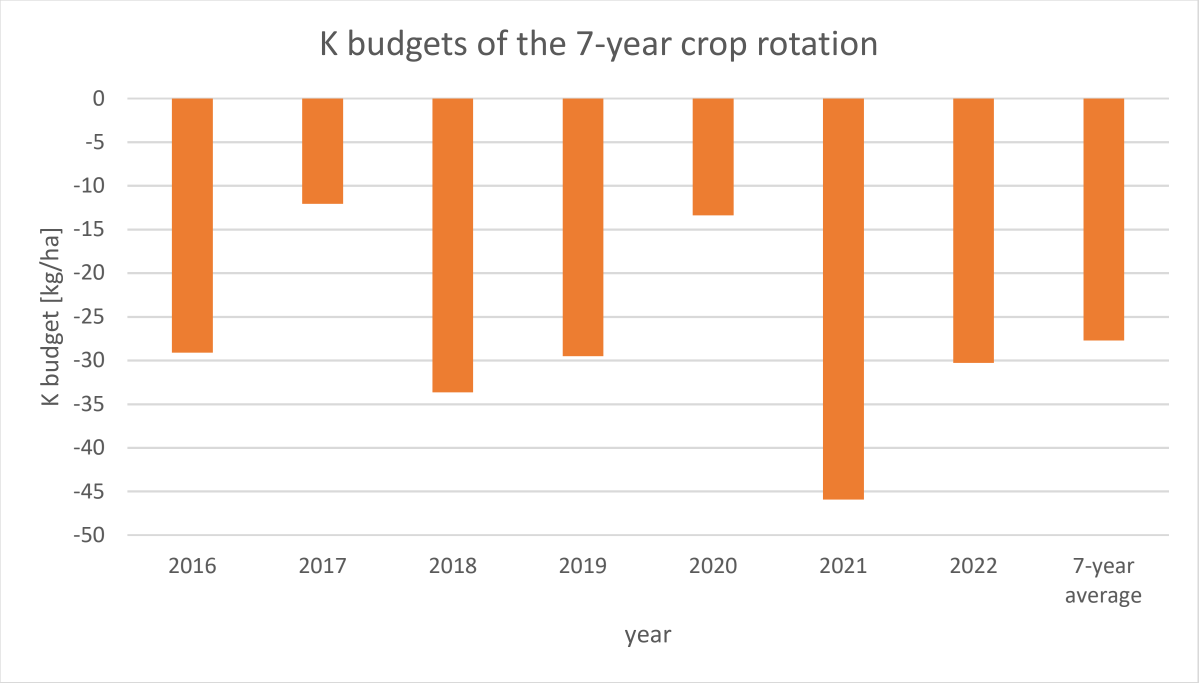


Figure 10: The K budget [kg ha^{-1}] of every year (2016-2022) and the 7-year average calculated with the input "Carbonated Lime" which contains a low K nutrient content (0,06 %).

As mentioned in chapter 1.1 Reimer et al. (2020a) showed that farms with a high reliance on BNF as main N input source had negative P and K budgets. This research therefore investigated if a similar relationship between BNF and (especially P or K) nutrient budgets emerges in the case of Kleinhohenheim. Kleinhohenheim used BNF as its only source of N input (besides marginal N inputs such as seeds) which is why an observable effect of BNF on the nutrient budgets was expected. And indeed, there was a correlation between BNF and nutrient budgets. The higher the share of N input from BNF of the total N inputs the higher was the N budget of the farm (Figure 11) because more N gets fixated by BNF. The coefficient of determination (R^2) also showed that the BNF could explain around half of the variation seen in the data. Other factors influencing the N budget could be the crop rotation and the yearly variation in yield and therefore output.

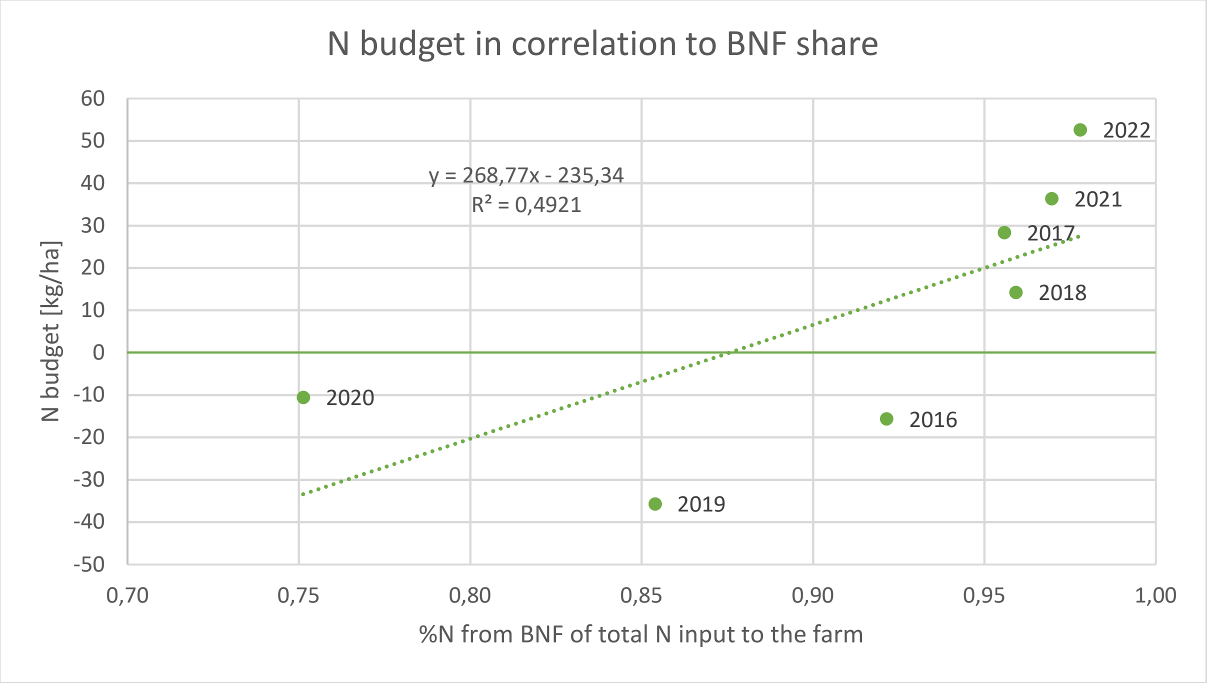


Figure 11: The N budgets [kg ha^{-1}] of every year (2016-2022) in relation to the BNF share of the total N input of the farm. A positive correlation can be seen. The higher the BNF share the higher the N budgets.

The P and K budget were expected to show a negative correlation to a higher BNF share. P and K leave the farm as crop exports and the CG which fixates N is sometimes exported as well so there is an additional P and K crop export. With no external fertilizers to replace the lost nutrients the BNF only accelerates the P and K depletion of the farm.

The results showed that P and K budgets were negatively influenced by a higher BNF share (Figure 12 and Figure 13). The higher the BNF share in a year the greater the P or K deficit. The coefficient of determination of the P budget was higher and of the K budget lower than the coefficient for the N budget.

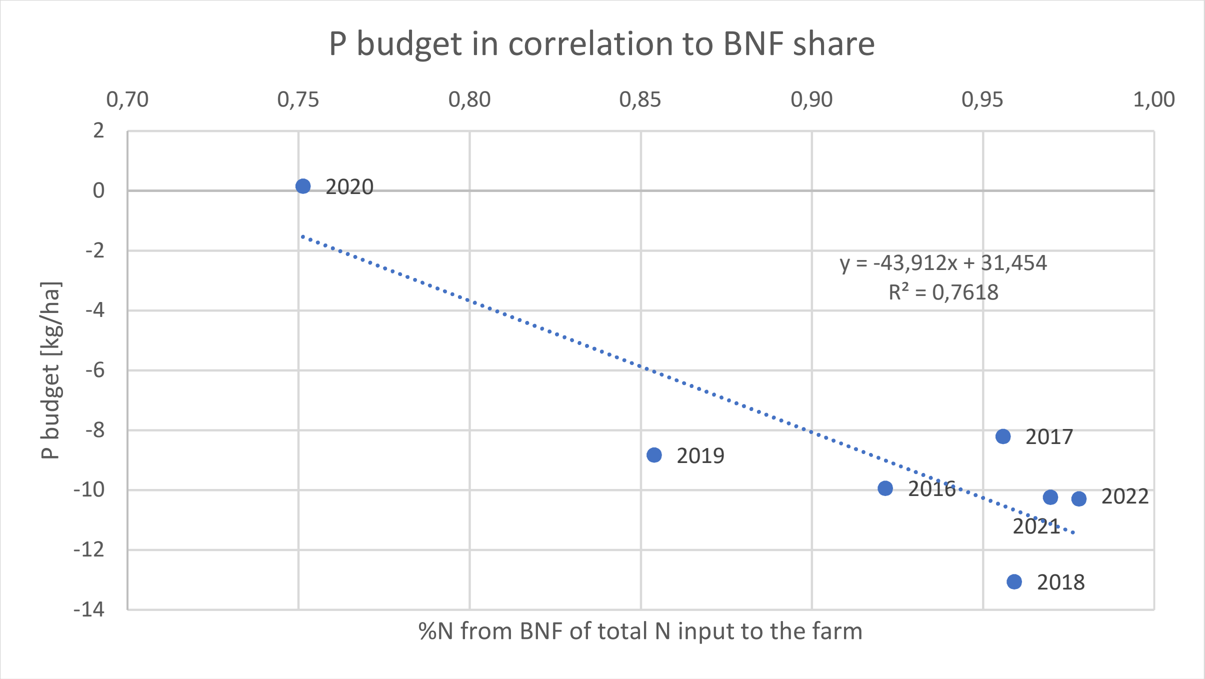


Figure 12: The P budgets [kg ha^{-1}] of every year (2016-2022) in relation to the BNF share of the total N input of the farm. A negative correlation can be seen. The higher the BNF share the greater the P budget deficits.

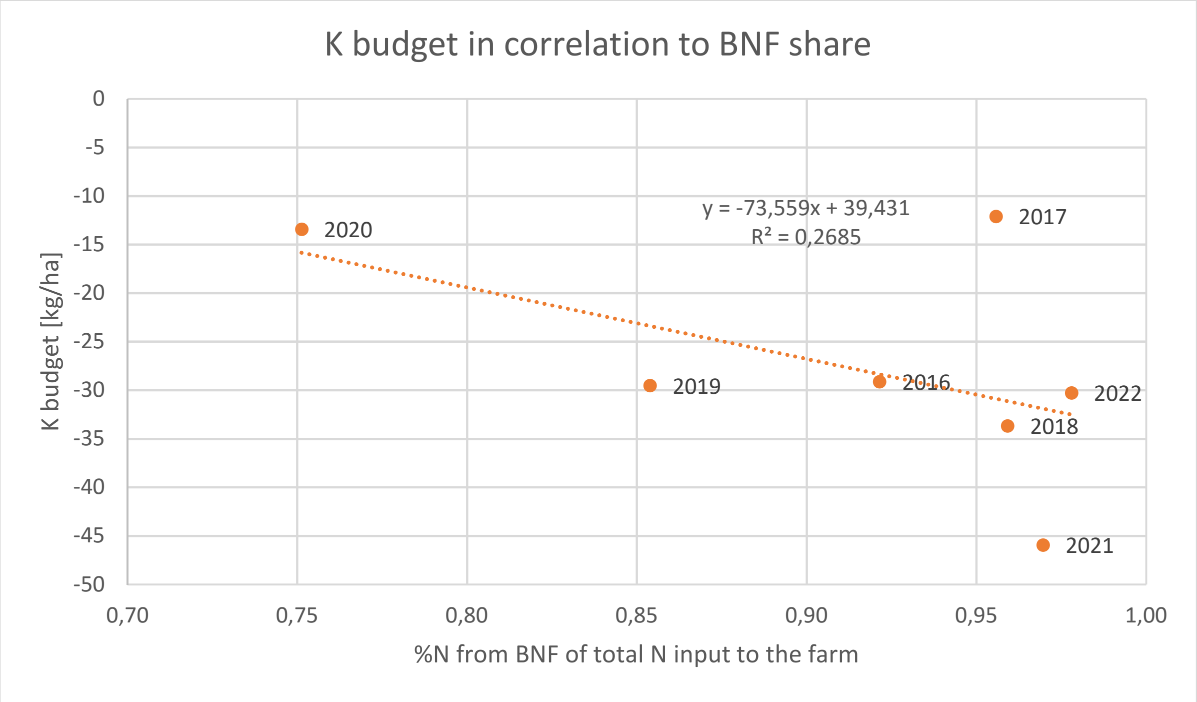


Figure 13: The K budgets [kg ha^{-1}] of every year (2016-2022) in relation to the BNF share of the total N input of the farm. A negative correlation can be seen. The higher the BNF share the greater the K budget deficits.

3.2. Nutrient field budgets of the current management

The field budgets can illustrate how nutrient budgets vary between the fields and if the overall nutrient budget of a field is positive or negative. Over the 7-year crop rotation most N field budgets are positive (not shown). This was due to the N inputs through BNF which Kleinhohenheim incorporated into the crop rotation for a continuous supply of N to the fields. The results also revealed that although most fields show a surplus of N over the 7-year crop rotation, KH8 showed a slight negative N budget.

It can be seen that the N budgets of every field varied between the years. Some years were more positive and others were more negative. This was due to different yields and therefore different amounts of nutrient outputs (cash crop exports) of the field and different amounts of nutrient inputs to the fields (BNF and CGS). While the yields of the crops determined the "actual" field output and N input (higher yield of BNF plants means a higher N input) to the farm the CGS could only shift nutrients between the fields. A higher application of CGS to one field could have increased this field's nutrient budget but the field where the CG came from lost these nutrients. This was especially the case for P and K as seen below.

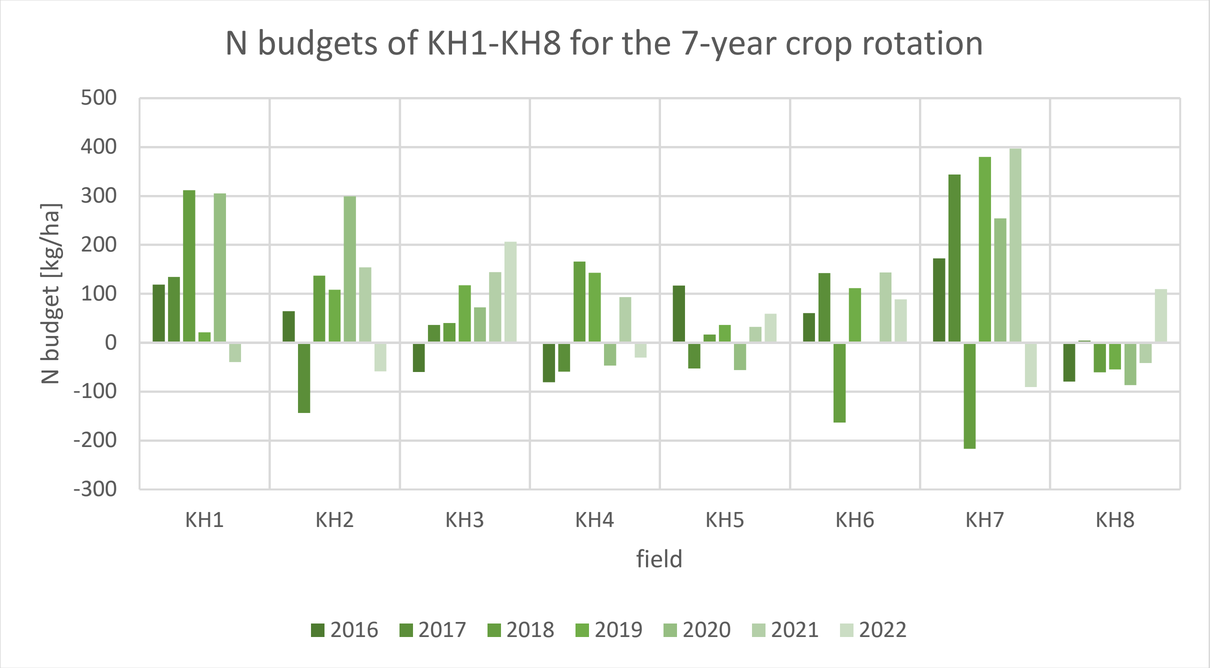


Figure 14: The N field budgets [kg ha^{-1}] of every year (2016-2022) is shown grouped for each field (KH1-KH8).

In most years the P field budgets were negative. There were years where some fields showed positive P field budgets (e.g. 2020 KH1 and KH2 or 2017 KH7) but averaged over the 7-year crop rotation every field except KH1 and KH3 had a negative budget (not shown). KH1's P budget was + 3,5 kg ha^{-1} year^{-1} and KH3's P budget was + 2,8 kg ha^{-1} year^{-1}. As described above this slight P surplus could only be explained with nutrient shifts because Kleinhohenheim did not import any external P fertilizer. The nutrients (in this case P) got shifted from one field to another by cultivating CG on one field, converting it to silage and then applying this CGS as fertilizer to another field in the following year. The exact fields between which the nutrients were shifted could not be assessed with the existing data. It could only be observed, that a P surplus could be achieved on some fields but the average P budget of all fields (Figure 17) stayed negative because there was no external P fertilizer which could replenish the exported P.

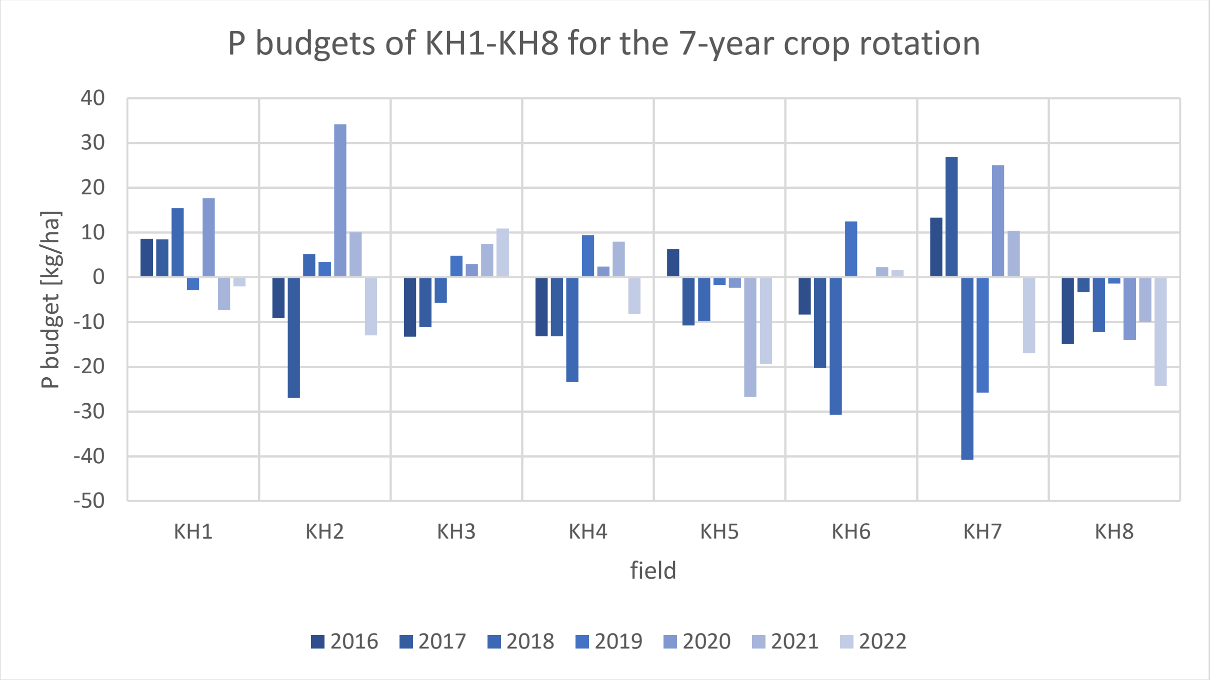


Figure 15: The P field budgets [kg ha^{-1}] of every year (2016-2022) is shown grouped for each field (KH1-KH8).

Similar to the P field budgets the average K field budget should also be negative because Kleinhohenheim did not import any external K fertilizer. However, most K field budgets were positive (Figure 16). All fields except KH4, KH5 and KH8 had positive K budgets averaged over 7 years (not shown). The negative field budgets were just slightly negative while the positive field budgets were highly positive which resulted in a positive average K field budget (Figure 17). This indicated that there was an unintended external K source which was included in the field budget calculations and therefore led to positive field budgets. The most plausible explanation was, that nutrient flows which were supposed to happen farm internally were actually not within the farm but came from external sources. The internal nutrient flow between fields should have been closed by converting CG into silage and applying the silage as fertilizer. However, it was not checked if the silage fertilizer inputs noted from Simon Schäfer and the data base were identical with the CG cuttings from the previous year. So, if there were more silage fertilizer inputs than could have come from the farm-grown CG outputs this would result in a net positive K budget. It is also possible that data for the CG cuttings were missing and this way not too many silage fertilizer inputs but instead too little CG cuttings were noted.

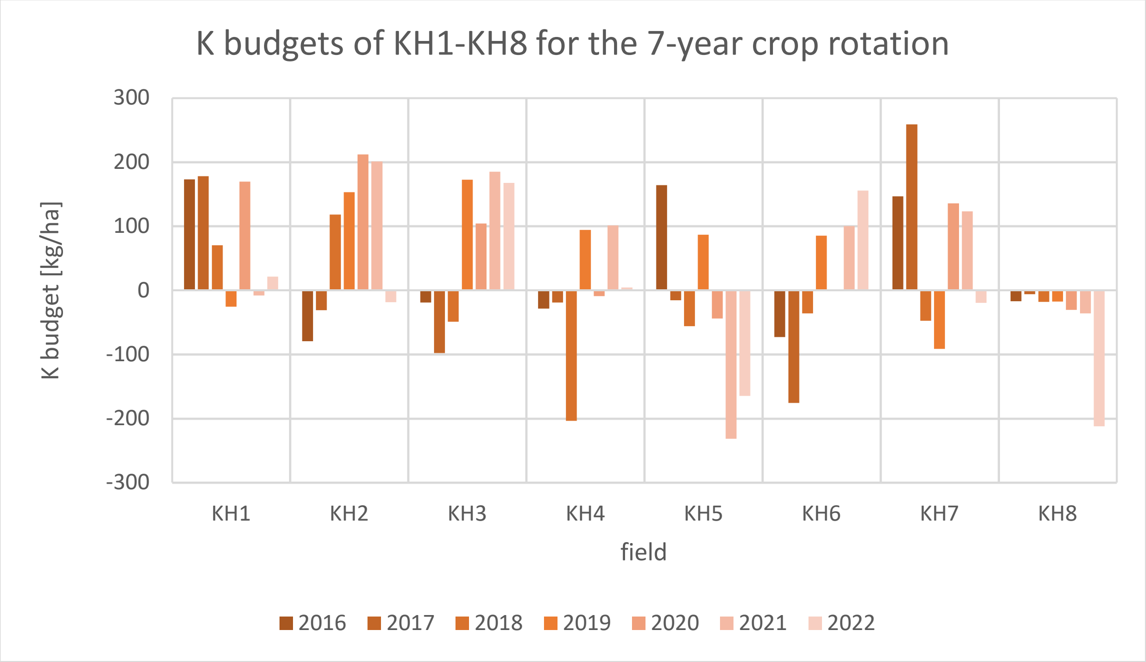


Figure 16: The K field budgets [kg ha^{-1}] of every year (2016-2022) is shown grouped for each field (KH1-KH8).

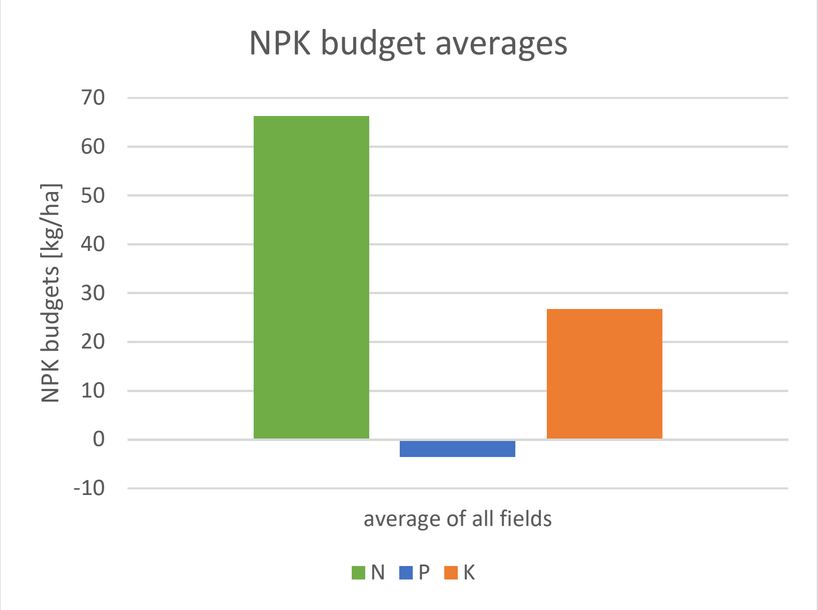


Figure 17: NPK field budget averages [kg ha^{-1}] of all fields (KH1-KH8).

The field budget results could also be shown as boxplots which could be used to examine the equal field management (same crop rotation, same fertilization regime, same yields and exports). Almost three quarters of KH8's boxplot was below zero and therefore KH8 had the most negative N budget (Figure 18). In general, the N field budget boxplots showed no great differences between the fields. This is an indication for a very similar field management regarding crop rotation and fertilization regime. It is interesting to note, that the yearly variation differed between fields. While KH7 had a boxplot distribution with a maximum of ~ +400 kg ha^{-1} and a minimum of ~ -200 kg ha^{-1}, there were also fields like KH5 which showed a boxplot distribution with a maximum of ~ +100 kg ha^{-1} and a minimum of -50 kg ha^{-1}. So, it is possible that in a given year the N budgets differed greatly between the fields but averaged over the 7-year crop rotation these differences in management evened out and the overall management strategy was balanced.

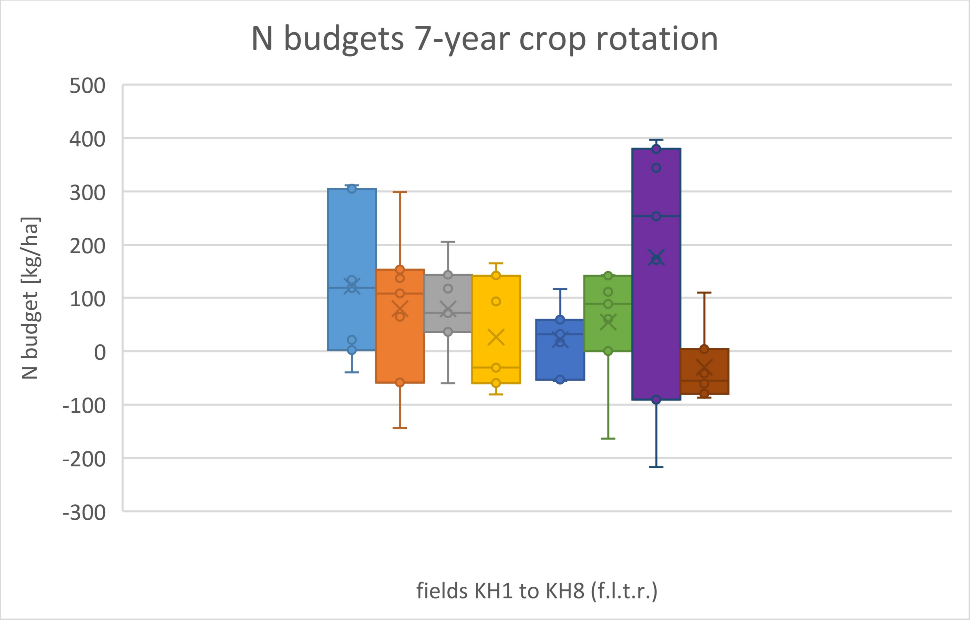


Figure 18: The N budget [kg ha^{-1}] of all years (2016-2022) pictured as a boxplot for each field (KH1 to KH8 (f.l.t.r.)).

Boxplots of the P field budgets also showed a balanced distribution of positive and negative budgets over the 7-year crop rotation per field. Most values fluctuated between ~ -30 kg ha^{-1} and ~ +20 kg ha^{-1}. The overall management of the fields seemed to be equal because there were no fields with only positive or only negative budgets. But a small decreasing trend from KH1 to KH8 was visible which showed that KH1 had an overall more positive P budget than KH8.

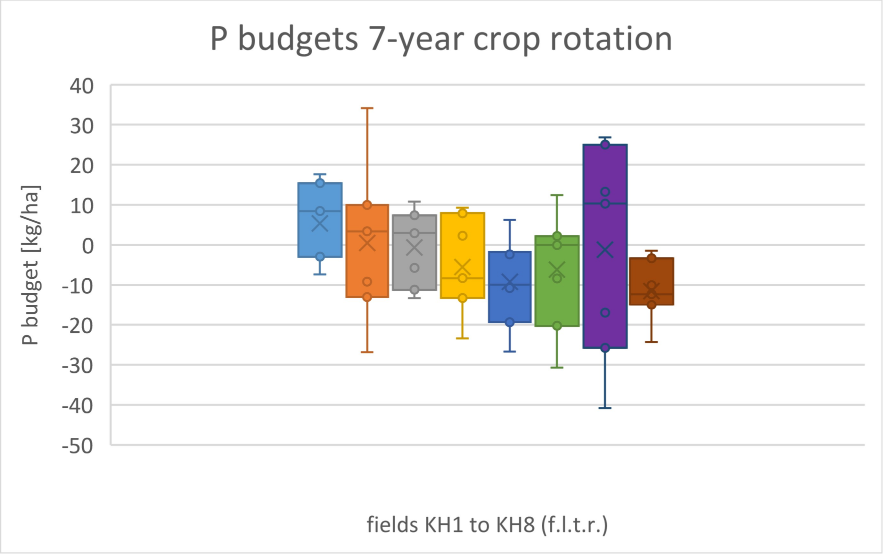


Figure 19: The P budget [kg ha^{-1}] of all years (2016-2022) pictured as a boxplot for each field (KH1 to KH8 (f.l.t.r.)).

The K budget boxplots were more positive than the P budget boxplots and were even similar to the N budget boxplots. Five out of eight boxplots had positive medians and positive averages (Figure 20). As already described in chapter 3.2 these positive K budgets could only be explained by errors in the data because there was no external K input that could have led to a positive average K field budget. Either too much CGS input must have been included or too little CG cuttings were included in the field budget calculations.

It could be observed that the field management regarding the nutrient K is also fairly equal. There were no great differences between the field budgets and most of them varied between ~ +200 kg ha^{-1} and ~ -150 kg ha^{-1}.

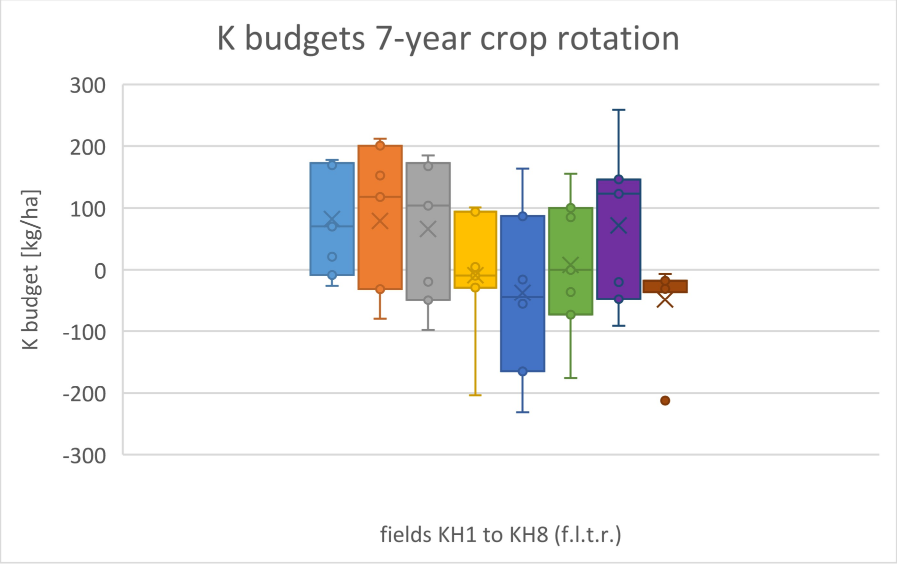


Figure 20: The K budget [kg ha^{-1}] of all years (2016-2022) pictured as a boxplot for each field (KH1-KH8 (f.l.t.r.)).

3.3. Nutrient farm-gate budget scenarios with fertilizer inputs

The N budget improved when any of the three fertilizers were used (Figure 21). BD and compost increased the N budgets of every year the most. Even though the total amounts of fertilizer imported differed between BD and compost the amount of N fertilized per ha was estimated and the same for both fertilizers (60 kg N ha^{-1}). This is why the N budgets of BD and compost have exactly the same results. Struvite was selected especially as a P fertilizer but could also raise the N budgets. Only in years where the current management resulted in very negative budgets (2019) struvite could not compensate the N deficit. In years with low negative budgets (2016 and 2020) struvite could improve the N budgets to become positive.

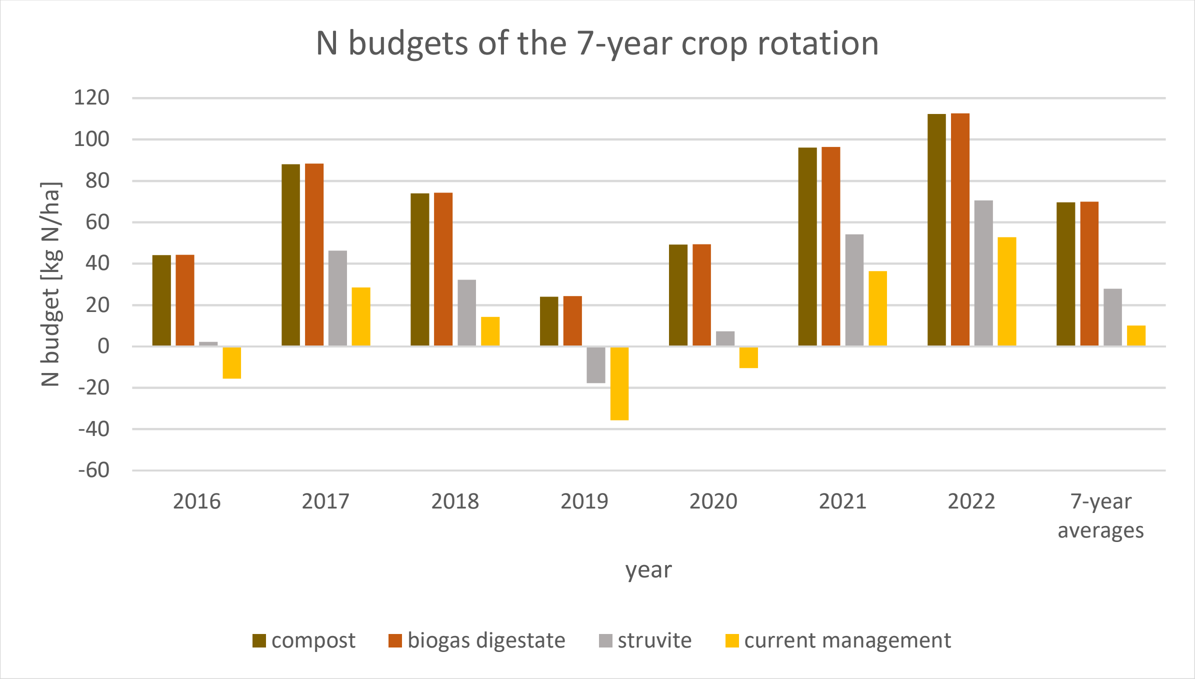


Figure 21: N farm-gate budgets with all three fertilizers and the current management for every year (2016-2022) to see the effect the three fertilizers have on the budgets.

The fertilizers also had different effects on the P budgets. Compost had a slightly more positive effect on the P budgets than BD (Figure 22) because it contained slightly more P (0,1 % more, see Table 4). Both fertilizers could raise the P budgets enough for the budgets to become positive (except 2018, which had the most negative budget under current management). But struvite increased the P budgets by far the most and resulted in a 7-year average of + 30 kg P ha^{-1}. Even in 2018 (with the most negative P budget under current management) the P budget increased from – 13 kg P ha^{-1} in the current management budget results to + 25 kg P ha^{-1} in the struvite scenario.

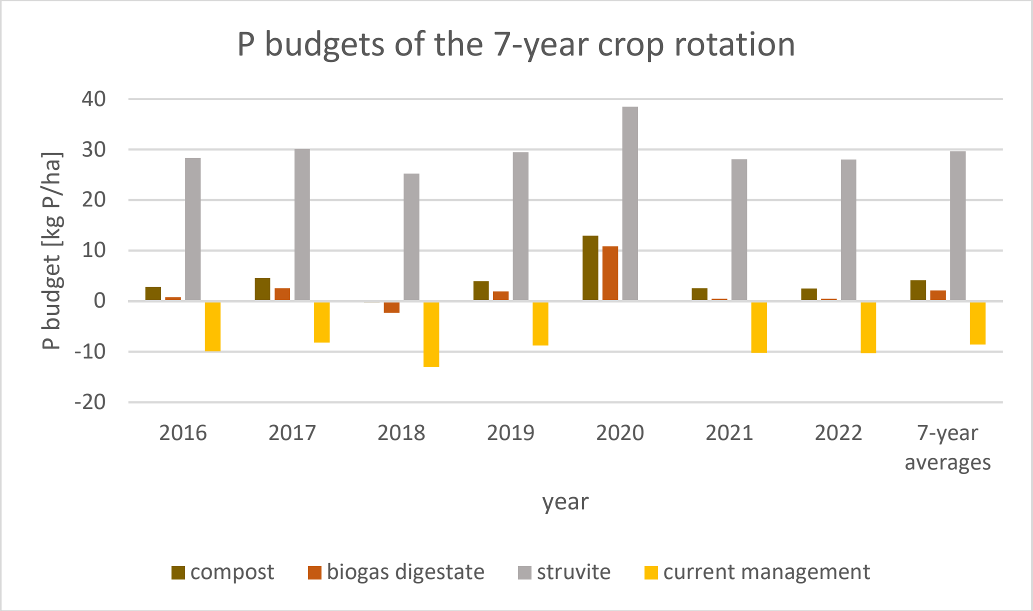


Figure 22: P farm-gate budgets with all three fertilizers and the current management for every year (2016-2022) to see the effect the three fertilizers have on the budgets.

The K budgets were only increased when BD or compost were used as fertilizer (Figure 23). BD always resulted in a + 7 kg K ha^{-1} higher budget than compost and could always compensate the nutrient deficits and therefore resulted in a positive K budget. When compost was used as fertilizer the K budgets almost always became positive (except 2021 because it had the most negative K budgets under current management). On the other hand, struvite did not have any positive effect on the K budgets at all. The K budgets stayed on the exact same level as under current management calculations. This is due to the very low K content in struvite.

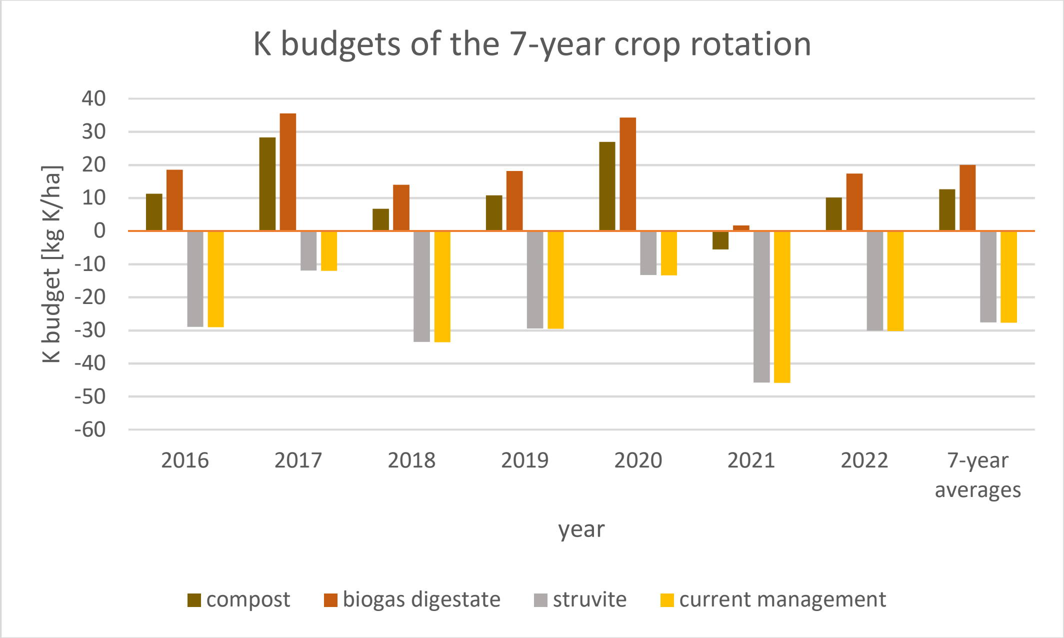


Figure 23: K farm-gate budgets with all three fertilizers and the current management for every year (2016-2022) to see the effect the three fertilizers have on the budgets.

When the 7-year averages of all three fertilizers and the current management were shown besides each other for every nutrient it became clear which fertilizer is most suitable for which nutrient (Figure 24). All three fertilizers elevated the average N budget even though it was already positive under the current management. Struvite only slightly increased the N budget while BD and compost increased the N budget a lot (from the average of the current management of + 10 kg N ha^{-1} to + 70 kg N ha^{-1} of the BD N budget). Although the average P budget became slightly positive when using BD or compost as fertilizer, struvite had the highest positive effect on the P budget. Compost could only increase the average P budget to + 4 kg P ha^{-1} (from – 9 kg P ha^{-1} of the current management) while struvite increased the P budget on average to about + 30 kg P ha^{-1}. The average K budget of the current management (- 28 kg K ha^{-1}) on the other hand could not be improved with struvite as fertilizer. Only BD and compost could compensate the K deficit of the current management and increase the average to a positive K budget. BD increased the average the most to + 20 kg K ha^{-1} (compost + 13 kg K ha^{-1}).

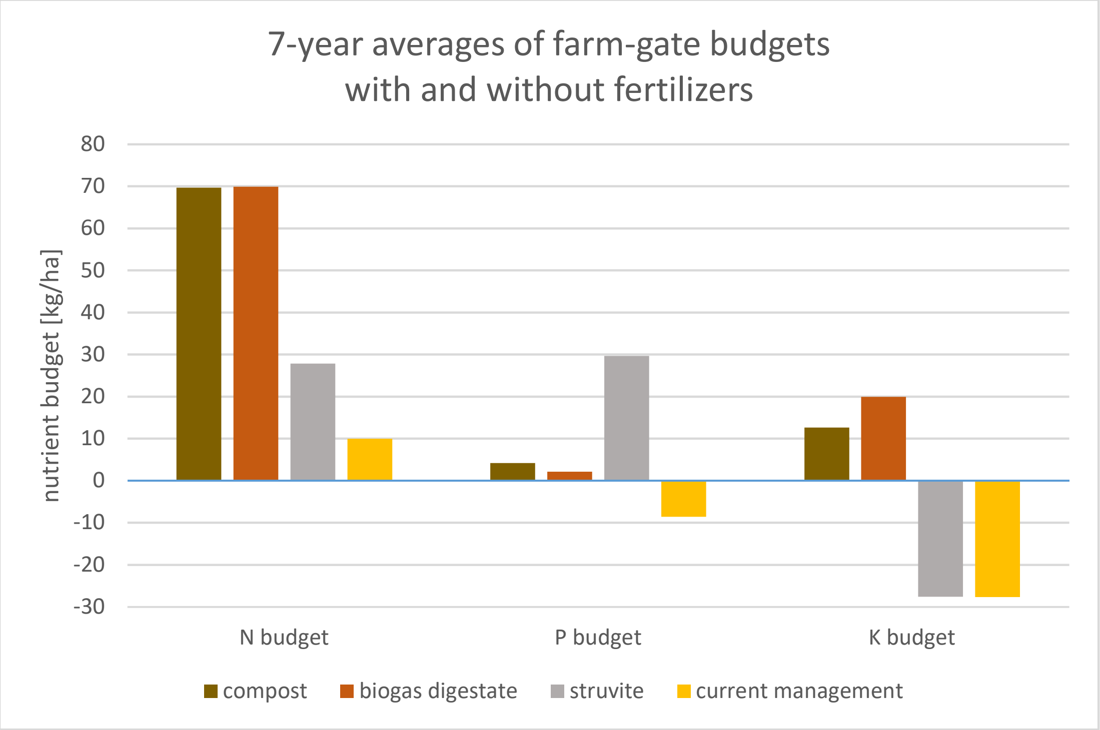


Figure 24: N, P and K 7-year average farm-gate budgets with all three fertilizers and the current management to see the effect the three fertilizers have on the average nutrient budgets.

3.4. SOM farm-gate budgets

The SOM farm-gate budgets were positive for every year in the researched seven years. The lowest positive budget was in the year 2016 with + 58 kg SOM-C per ha (little data was available for this year) and the highest budget was in 2022 with + 243 kg SOM-C per ha which can be seen in Figure 25. The 7-year average for the SOM budgets was + 141 kg SOM-C per ha. It can be seen that there were variations between the years. The differences between the years could be explained by the different yields and therefore different amounts of by-products which were the main source for SOM reproduction for Kleinhohenheim. 2017, 2018 and 2022 had the highest yields and therefore a lot of SOM reproduction through by-products (step 2 of the program).

The program suggests that the SOM budgets should be between – 75 kg C ha^{-1} year^{-1} and + 125 kg C ha^{-1} year^{-1}. According to this evaluation system the SOM farm-gate budgets of 2017, 2018 and 2022 are too high but the different evaluation systems with which the SOM budgets can be evaluated will be discussed in chapter 4.6.

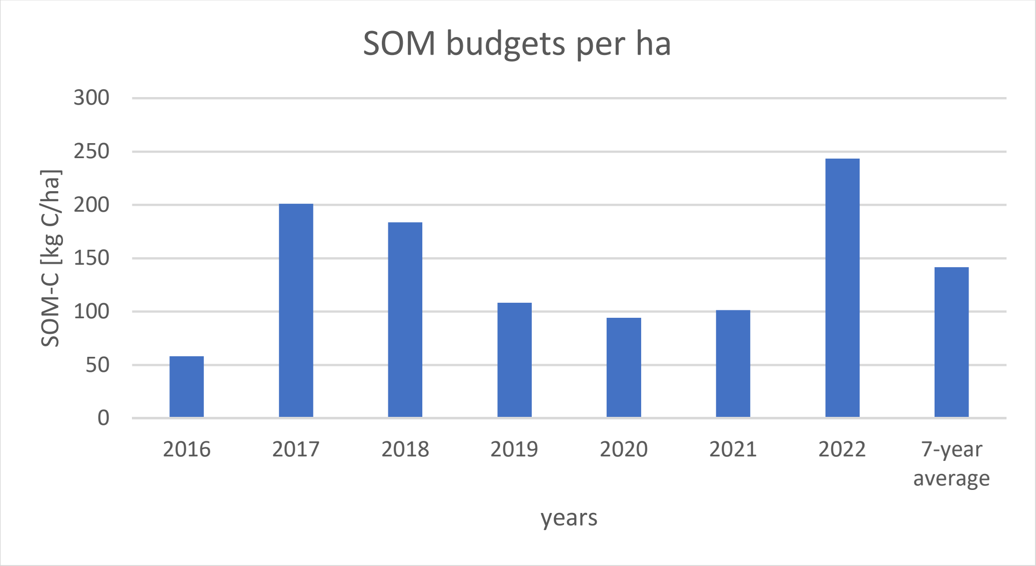


Figure 25: SOM budgets [kg SOM-C ha^{-1}] of every year (2016-2022) and the 7-year average.

When taking a more detailed look at the factors which played a role in the SOM budget calculations, it became clear that the crops almost always (except 2022) had a negative effect on the SOM budget (Figure 26, red bars). On the other hand, the crops' by-products (dark green bars) had a positive effect on the SOM budget. The SOM reproduction of the crops' by-products alone compensated the SOM loss through the crops which resulted in an average positive budget for every year (yellow bars which are basically the bars of Figure 25). There were no visible light green bars which would have represented the OM applied to the fields because the only OM used in Kleinhohenheim was CGS and the farm-gate budgets were calculated without it as explained in chapter 2.3.4.

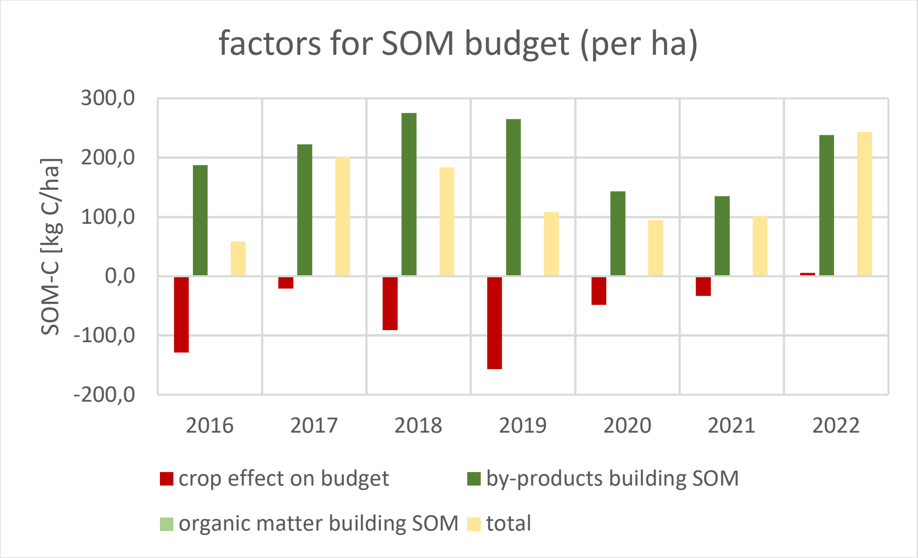


Figure 26: The total farm-gate budget (yellow bars) and three factors which were used to calculate the total SOM budgets [kg SOM-C ha^{-1}] listed for every year (2016-2022). The three factors include the crops (red bars), the crops' by-products (dark green bars) and the applied organic matter's (light green bars) effect on the SOM content.

The 7-year average of the factors emphasized the clear difference between SOM diminishing (SOM loss through cultivating crops) and SOM reproducing factors (crops' by-products). Cultivating and selling crops led to a SOM loss and the crops' by-products were essential for SOM reproduction. Because there was more SOM reproduction than SOM loss the sum of the two factors resulted in a positive SOM farm-gate budget in total.

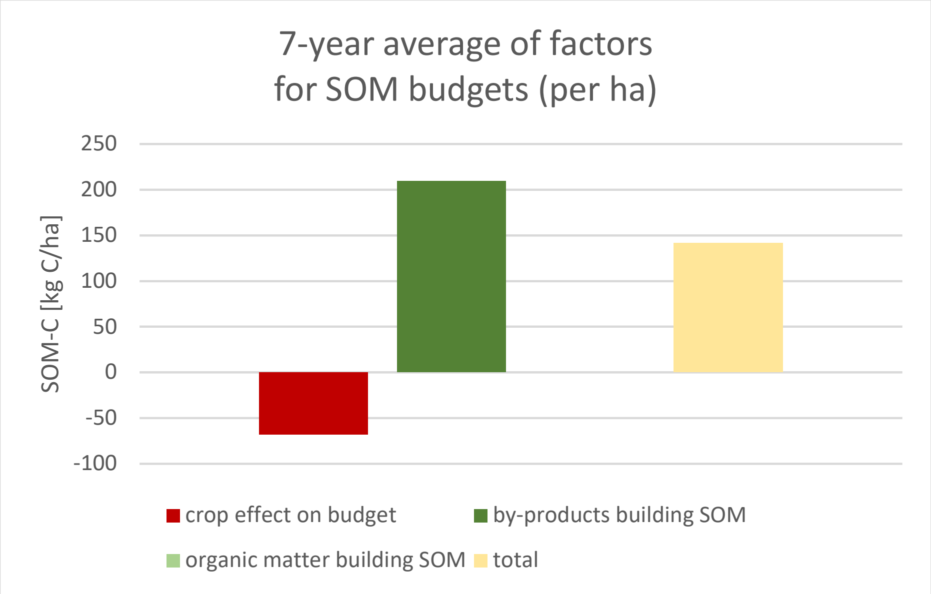


Figure 27: The 7-year average SOM budget [kg C ha^{-1}] (yellow bar) and the 7-year average of the factors influencing it (red and dark green bar).

3.5. SOM field budgets

The SOM field budgets showed similar results. All fields had a positive SOM budget per ha per year (Figure 28). It is interesting to note, that the average of all fields (+ 204 kg SOM-C ha^{-1} year^{-1}) was higher than the farm-gate 7-year average (+ 141 kg SOM-C ha^{-1}) as seen above because CGS was included in the field budget calculations. KH3 and KH7 had the highest SOM budgets with + 306 kg SOM-C ha^{-1} year^{-1} and + 286 kg SOM-C ha^{-1} year^{-1} while KH8 had the lowest positive (+ 64 kg SOM-C ha^{-1} year^{-1}) SOM budget by far. According to the SOM budget evaluation system of the program the SOM budgets of every field except KH8 was above the maximum value of the range for acceptable SOM budgets (budgets should be between – 75 kg SOM-C ha^{-1} and +125 kg SOM-C ha^{-1}). Hence, KH1 to KH7 had exceptionally high SOM contents according to the program.

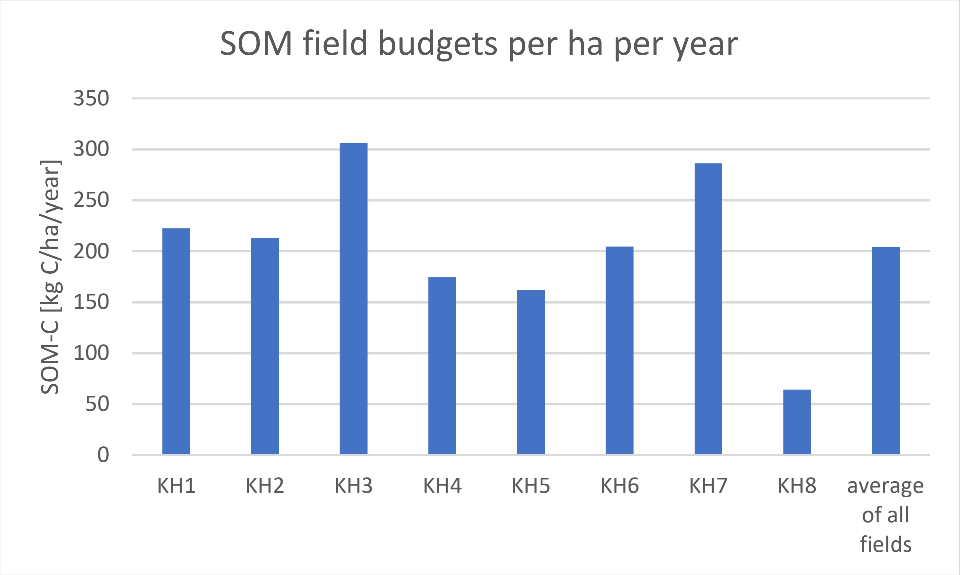


Figure 28: SOM budgets [kg SOM-C ha^{-1} year^{-1}] of every field (KH1 to KH8) and the average of all fields.

The factors from which the field budgets were calculated showed similar results as the farm-gate budget factors. The cultivation of crops led to a SOM loss while the crops' by-products had a SOM reproducing effect on the budget. Additionally, there was OM applied to the fields (CGS) which also reproduced the SOM. Because the field budgets were already positive through the crops' by-products which reproduced more SOM than was lost through the cultivation of crops, the OM applied to the fields increased the total field budget even more.

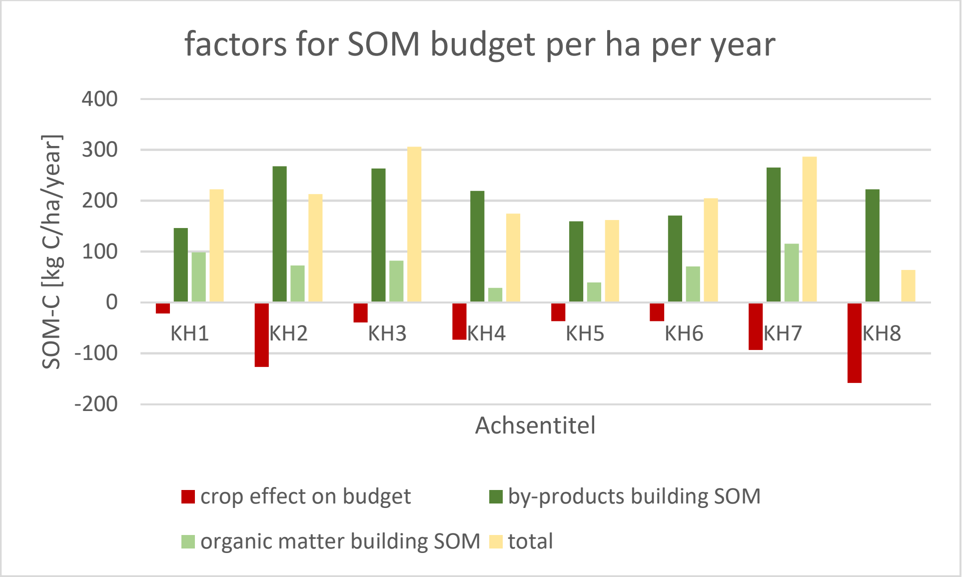


Figure 29: The total field budgets (yellow bars) and three factors which were used to calculate the total field budgets [kg SOM-C $\mathrm{ha}^{-1}\ \mathrm{year}^{-1}$] listed for every field (KH1 to KH8). The three factors include the crops (red bars), the crops' by-products (dark green bars) and the applied organic matter's (light green bars) effect on the SOM content.

4. Discussion

4.1. Nutrient budget calculations

The Excel tool which was used to calculate the nutrient budgets is based on literature and standard values for nutrient contents of the in- and outputs. Additionally, for the budget calculations of this research further data had to be estimated from literature (Table 4). These standard values and estimations are not the actual nutrient contents of the in- or outputs, so nutrient budgets are always subject to uncertainties in this regard. The best example of this problem was the carbolime input which was included in the calculations as the program's default "Carbo lime" which had an ~18 % K content which distorted the K budgets towards very positive results. During the evaluation of the results this high impact of carbolime on the K budgets was a cause for suspicion that the program could have overestimated the effect of carbolime. The very high K content of carbolime contradicted other literature data such as the data from Möller and Schultheiß (2014) which specify only 0,06 % of K in carbolime. This is why the K budgets (and all the other farm-gate and field budgets) were adjusted and calculated again with carbolime with the nutrient content data from Möller and Schultheiß (2014).

Another source of uncertainties regarding the nutrient budget results is the data from Kleinhohenheim used for the budget calculations. On the one hand, mistakes made by Simon Schäfer while bookkeeping cannot be ruled out and on the other hand, Simon Schäfer had to estimate certain values himself when there was no accurate data at all. The data acquired from the data base of the university was not checked for correctness with the previous manager of Kleinhohenheim and therefore the accuracy of this data is also subject to uncertainties.

One method to calculate BNF is the multiplication of the total yield of the nitrogen fixing plant with a simple transformation factor. This simple BNF calculation method is often used by farmers because it is easy to implement. While it was shown by Kolbe (2009) that this method underestimates the amount of N fixation by crops with high BNF rates and overestimates the amount of N fixation by crops with low BNF rates (for red clover this underestimation could be up to 100 kg N ha^{-1}) it was also shown that another adjusted method called "Saldo-Rechner" does not have this problem. This "Saldo-Rechner" method is used by the program to calculate the BNF but still tends to overestimate the N fixation of red clover by ~ 60 kg N ha^{-1}. Red clover was the main source of BNF input for Kleinhohenheim which is why the BNF input might have been overestimated. Both an underestimation and an overestimation could mislead nutrient budget result interpretations. The underestimation of the BNF input could give the impression that the import of fertilizers is necessary to improve the seemingly low N budget. But actually, there was more BNF than calculated and the positive N budget and N soil content is adequate and additional N inputs through fertilizer imports could create an oversupply of N resulting in adverse environmental effects such as N leaching. An overestimation of BNF could give the impression of an adequate N supply to the farm while in reality there is less N in the soil than calculated which could result in lower yields. There would also be other methods which could achieve better results but in practice these methods are difficult to use because they are too complex and not user-friendly (Kolbe, 2009). The scope of this research had to be limited to this "simple" Excel tool which is why an uncertainty regarding the actual amount of N fixated on the fields of Kleinhohenheim remains.

Further, BNF as the sole source of N inputs to Kleinhohenheim poses a risk because BNF is dependent on soil moisture, nutrient availability, diseases and yield level (Anglade et al., 2015a). Therefore, a dry year affects the whole farm: less N is fixated by legumes and consequently there is less N available for the cash crops which results in lower cash crop yields. A diversification of N inputs through organic fertilizer imports could ensure a steadier N supply and would reduce the susceptibility of Kleinhohenheim to BNF fluctuations. Possible fertilizers for Kleinhohenheim are discussed in chapter 4.4.

4.2. Nutrient budget results

The nutrient farm-gate budget results of this research confirmed previous findings of Reimer et al. (2020b). Regardless of farm type OFs showed positive average N budgets and negative average K budgets and this research confirmed these results. The only difference were the P budgets which were balanced in Reimer et al. (2020b) and negative in this research which can be explained by the higher nutrient inputs to the OFs analysed by Reimer et al. (2020b) compared to no external P inputs to the Kleinhohenheim farm. The trend that average N budgets were highest (positive), followed by P budgets (balanced) and with the K budgets at the end with the lowest (and negative) budget was also visible in the average budget results of this research (in descending order): N budgets (positive) > P budgets (slightly negative) > K budgets (most negative). Arable (stockless) and mixed OFs had the most problems with nutrient deficits (Reimer et al., 2020b) and even though there was no comparison drawn to other farming types in this research this observation could also be confirmed because Kleinhohenheim as an arable stockless OF had more negative P and K budgets than the P and K budgets from Reimer et al. (2020b).

Even though N farm-gate budget results were positive (Figure 7) this does not necessarily mean that the crops were adequately supplied with N. One of the main yield restricting factors of OA is the N availability especially at specific time periods e.g. when crops are in their growth phase (Berry et al., 2002). So, yields might be increased by improving the N availability to the crops by applying (organic) fertilizers with a high N availability at the optimal time to the fields (discussed in chapter 4.4).

Kleinhohenheim relies completely on BNF as its only N source making the P and K farm-gate nutrient deficits an even more urgent issue because Reimer et al. (2020a) showed that a high reliance on BNF for N inputs results in greater P and K deficits. This correlation was supported by the findings of this research. The higher the BNF share of the total N input to the farm the greater the P and K deficits. The very low coefficient of determination indicated that there was too little data points (seven nutrient farm-gate budgets) to reliably determine the BNF as the sole factor influencing the P and K nutrient budgets (Figure 11, Figure 12, Figure 13). More data points would be needed to see if there are other unknown factors influencing the P and K budgets.

One explanation for the greater P and K deficits when BNF makes up a large share of the total N input to the farm is the need of the N fixating plants for P and K for their growth (Römer and Lehne, 2004). When the aboveground biomass of the N fixating plants was exported P and K left Kleinhohenheim and was not replenished by external fertilizers.

The nutrient field budget boxplots showed similar medians and averages of all fields. The boxplots of KH1, KH2, KH3, KH6 of the N budget were almost the same, however small differences between the fields KH4, KH5, KH7 and especially KH8 could be seen (Figure 18). KH8 had the lowest budget average for all nutrients (Figure 18, Figure 19, Figure 20). Furthermore, all nutrient field budget boxplots showed a trend of decreasing averages from KH1 to KH8 (Figure 18, Figure 19, Figure 20). KH1 almost always had the highest average and KH8 always had the lowest average. The small differences and the decreasing trend between fields showed that there was still potential to improve the field management to achieve equal treatments of all fields. Accurate planning, implementation and documentation of field in- and outputs would be needed to be able to monitor the success of a more equal treatment of the fields.

The differences between the field budgets could also be explained by the observed crop rotation time period. KH8 seemed to have been treated differently because it had a negative N field budget. But the observed time period (2016-2022) contained only one N fixating crop (CG) that was freshly sown, so it could only fixate a small amount of N. Even though lentils grew on KH8 in 2017 instead of silage corn or potatoes, lentils fixate not as much N as CG (CG > lentils > field pea) (Kumar and Goh, 2000; Liu et al., 2019) and therefore did not improve the overall N budget. The crop rotation of KH8 was implemented differently than originally planned (Table 5). In 2019 winter rye grew on KH8 instead of broad bean which resulted in even less BNF. So, the perceived differences between fields might be due to the observed time period and the deviations from the crop rotation plan.

Table 5: The crop rotation of KH8 as planned and actually implemented. Source: Simon Schäfer, modified, Appendix IV

Crop rotation of KH8	2016	2017	2018	2019	2020	2021	2022	2023
planned	WW	Silage corn or potato	Summer cereal	Broad bean	Spelt	Rye	CG	CG
implemented	WW	Lentils	Oats	Rye	Spelt	Rye	CG	Not included in budgets

4.3. Nutrient budget results compared to soil analyses

A reliable way of assessing the plausibility of the budget results is a comparison to soil analyses, to see if the budget calculations coincide with the soil nutrient contents. If the budget results and soil analyses are similar it shows that the nutrient budgets were able to predict the actual nutrient supply of the farm. The budgets could then be used to establish future strategies for Kleinhohenheim to further improve the nutrient supply towards an optimal supply to ensure soil fertility and prevent nutrient losses.

P and K budgets were compared to the soil analyses because they were most important because of the low supply to Kleinhohenheim and the resulting deficiencies of these nutrients.

N budgets were not compared to soil analyses because no nutrient deficiency for N was found in the budgets. Table 2 shows the P_2O_5 and K_2O content of the fields in 2016 and 2021 and groups them into “content classes” which rate the content of this nutrient in the soil (Table 1). In 2021 the P content is classified as low for most fields, two times classified as optimal (KH3 and KH4) and once classified between low and optimal (KH7). The K content is classified as low for most fields, once classified as very low (KH6) and once classified between low and very low (KH8) in 2021. This is in line with the P and K nutrient farm-gate budgets which were negative for all years. This nutrient depletion becomes apparent in the low or even very low P and K nutrient contents in the soil samples.

In 2016, however, the P content classes were almost all optimal except KH2 and KH8 which might indicate that the average P content of the soil decreased rapidly from “C = optimal” to “B = low” in the five years between 2016 and 2021. It has to be noted, that measuring P soil content with the Calcium-acetate-lactate (CAL) extraction method is subject to variations because soil properties influence the extraction efficiency of this method (Wuenscher et al., 2015). So, the differences between the two soil samples from 2016 and 2021 might seem larger than they actually are due to measurement variation. Still, a P deficit in Kleinhohenheim can already be seen with only the soil analysis from 2021 which confirm the P budgets.

The K content classes did not change that much from 2016 to 2021. The only fields which experienced a decrease in content classes were KH2 (from C to B) and KH8 (from B to A). The lower discrepancy between the two samples (compared to the differences of P budgets and soil analyses) may be due to varying soil physical, chemical or biological activities (microorganisms and plant activities) (Zörb et al., 2014) which might have increased K contents in 2021, resulting in similar results to 2016. According to these soil analyses K depletion poses less of a risk than P depletion to Kleinhohenheim, even though the K budgets were more negative than the P budgets. Manning (2009) explains that K is also present in the soil in the form of minerals which might supply K to the soil and could be a reason for adequate K contents measured in soil analyses. So, the soil analyses could show sufficient K content of the soil but this does not change the unsustainability of continuous K offtake through crops without compensating the K loss by importing fertilizers. Even though the soil analyses do not indicate a K depletion of the soil, the negative K budgets of this study confirmed that the K nutrient management of Kleinhohenheim is unsustainable because no external K fertilizers are used to compensate the K losses.

Furthermore, the CAL extraction method used for P and K content measurement cannot predict how much of the nutrients are plant available (Wuenscher et al., 2015). Therefore, even optimal content classes do not necessarily represent an optimal supply of P and K to the plants.

4.4. Suitable fertilizers for Kleinhohenheim to improve nutrient farm-gate budgets

By importing fertilizers positive nutrient budgets could be achieved (Nesme et al., 2012; Oelofse et al., 2010). This research confirmed these findings. The hypothesis that the three fertilizers would compensate P and K budget deficits was mostly confirmed (struvite only compensated P deficits). N budgets also increased with any of the three fertilizer inputs. The three fertilizers had different effects on P and K farm-gate budgets. Struvite increased P budgets the most but did not change K budgets. BD increased K budgets the most and also led to positive P budgets (except slightly negative budgets 2018). Compost increased P budgets slightly more and the K budgets slightly less than BD. So, struvite only seems to be suitable for compensating the P losses but not K losses while BD and compost are suitable for compensating both P and K losses.

The nutrient budget scenarios with fertilizer inputs may indicate if a fertilizer could compensate nutrient budget deficits but there are also many other factors which are important for evaluating the suitability of a fertilizer.

One main objective of OA is to close nutrient cycles. According to the OA principles a sustainable fertilizer should close nutrient cycles and come from organic and natural sources (IFOAM, 2017). Theoretically, this objective can be achieved by compost and BD depending on what source material was used. When CG or municipal household waste is used as substrate for biogas production or composting, BD and compost applied as a fertilizer close nutrient cycles. Furthermore, compost and BD are from natural sources while struvite is not. An advantage of struvite is the nutrient cycle closure on a bigger scale which is between urban environments and farms (Steinmetz et al., 2023) while compost and BD can only be used regionally because of their great volume which would make long transports uneconomical.

Recovered struvite from wastewater streams could substitute up to 20 to 30 % of the current mineral P fertilizer in Germany which emphasizes the potential of struvite to close nutrient cycles on a bigger scale (Cooper et al., 2018; Steinmetz et al., 2023).

Another fertilizer characteristic which is also crucial for evaluating the suitability of a fertilizer is the nutrient availability of the fertilizer. In chapter 1.2. the nutrient availability of the fertilizers was briefly outlined. The following section covers other factors to consider when assessing fertilizer suitability.

While compost resulted in increases in nutrient availability (Duong et al., 2011; Wilson et al., 2019) the main benefit for soil fertility of compost application was found to be non-nutrient benefits. Especially in dry years the non-nutrient effect of compost on soil fertility is higher than the actual nutrient input through compost because compost improves soil characteristics such as the SOM content which itself improves e.g. water holding capacity leading to higher yields (Stukenholtz et al., 2002). But this non-nutrient effect of compost application may only have (yield) benefits in the long-term because in the short-term it did not increase yields (Wilson et al., 2019). Furthermore, this research did not take non-nutrient effects of compost into account.

Stukenholtz et al. (2002) found a grain yield increase with compost fertilization amounts between 10 t ha^{-1} and 25 t ha^{-1}, much higher than the fertilization amount used in this research (6,38 t FM ha^{-1}). The fact, that compost might only increase yields in the long-term and that the here used fertilization amount was less than that of Stukenholtz et al. (2002) showed that even the positive nutrient budgets after compost application (of this research) are unlikely to result in short-term yield increases for Kleinhohenheim (Wilson et al., 2019). This reduces the economic benefit of compost fertilization.

It is also difficult to draw conclusions about the feasibility of biowaste compost (used in this research) based on previous studies because depending on the compost properties the effects on soil fertility can vary widely. Many studies mentioned in chapter 1.2.1 did not include biowaste compost, so the effect of biowaste compost on the soil fertility and nutrient status and availability might differ from the composts in the studies. Field experiments with compost fertilization on Kleinhohenheim fields could help to determine the actual effect of biowaste compost on the nutrient status of the fields because they include all the different factors and interactions between compost, soil, management strategy and climate which influence the fertilization effect of compost (Adugna, 2016).

BD has a very good nutrient availability (Gómez-Brandón et al., 2016) and increased all nutrient budgets calculated in this research. Additionally, the fertilization of plants with BD can be much more targeted compared to CG residues left on the field or incorporated into the soil (Erhart et al., 2014; Stinner et al., 2008). Therefore, BD is the most suitable fertilizer for Kleinhohenheim based on this research. But Golovko et al. (2022) reported chemical pollutants in BD but their adverse effects on humans and the environment are not well enough researched yet. Furthermore, some pathogens survive the very high temperatures of the AD process and can be found in BD which could pose health risks when BD is applied as a fertilizer. This is why more research is needed to be able to better assess the risks of BD fertilization (Golovko et al., 2022).

Even though experiments with struvite yielded promising results regarding P availability to the plants further research is needed because most existing experiments are pot experiments and need to be replicated on a field scale. These experiments would also have to be long-term experiments because P processes in the soil are slow and P content changes are only observable over long time periods (Römer and Steingrobe, 2018). Wollmann and Möller (2018) already showed in a field experiment on an OF that even though there was P supplied to the plants by the struvite fertilizer it was not a significant difference between struvite fertilized and unfertilized treatments. P availability of struvite is also dependent on soil pH and soil type which is why more research regarding improvement of P dissolution of struvite is needed to make struvite usable under different soil conditions (Nongqwenga et al., 2017). Additionally, the effect of struvite application from field experiments might be overestimated because experiments usually use high P application rates (Hertzberger et al., 2020).

Furthermore, struvite did increase the yields in the following two years after its application more than in the application year which shows the potential of struvite as a long-term fertilizer (Thiessen Martens et al., 2022). Kleinhohenheim could compensate the P deficits by applying struvite only once every three years making the application more economical viable compared to yearly fertilizer applications. It was also shown that struvite is most effective when the soil has a low initial P content (Nongqwenga et al., 2017). So, struvite fertilization would be very efficient in Kleinhohenheim because almost all fields had low soil P contents in 2021 (Table 2).

The literature about the effects of struvite fertilization and adequate fertilization recommendations for struvite is insufficient and inconclusive regarding effects on yield, belowground biomass, belowground P uptake and changes in P soil content (Hertzberger et al., 2020). Kleinhohenheim could therefore use struvite on an experimental basis to be able to evaluate struvite as a P fertilizer. Besides monitoring the success of struvite in compensating P deficits the experiments could help identify optimal application rates and more knowledge about the adequate use of struvite would be gained.

The limited scope of this research did not allow for a complete overview over the existing literature of the fertilizers used in this research. This is why mostly nutrient availability was the basis on which fertilizer recommendations were given. But many factors have to be considered to be able to recommend fertilizers such as environmental concerns, economic viability and regional availability of the fertilizer. Further literature screening and even more research about all these factors and fertilizer characteristics is needed to give substantiated fertilizer recommendations.

Lastly Reimer et al. (2020a, 2020b) mentioned the problem that fertilizers do not supply nutrients in the exact amounts the plants need. This could cause deficiencies of one and oversupply of another nutrient resulting in unbalanced nutrient budgets even though fertilizer is imported. This phenomenon was also observed in this research. Struvite for example led to a great P surplus while K budgets were still negative. To avoid this problem, different fertilizers should be combined to better meet the nutritional needs of the plants (Reimer et al., 2020b).

4.5. Soil organic matter budget calculations

The SOM budget calculations were carried out with an Excel tool which was last updated in 2006. According to one of the developers of the program, Werner Schmid (pers. comm.), the program may contain some outdated data or does not include certain data at all. Kleinhohenheim using CGS as a fertilizer is a very recent development in OA which is why there is no data about the SOM-RC of CGS. A range for the CGS SOM-RC was given by Kolbe (2013) from which the median value was taken for this research (Table 4). In the end, these estimated values were not used in the budget calculations because firstly, it was assumed that the farm-gate budgets already include the SOM reproduction in step 1 when CG is grown and left on the field and secondly, the field budgets were calculated with "Grünschnitt" as an OM input in step 2b because all field budgets were already positive with this input. The SOM field budgets would be much higher with CGS with 115 kg SOM-C t^{-1} as an OM input instead of 16 kg SOM-C t^{-1} (from "Grünschnitt") and could be rated as optimal or too high depending on the evaluation system used for SOM budget evaluation (discussed in chapter 4.6).

It is also not possible to specify if the cuttings (of e.g. CG) were left on the field or used to make CGS. Because CGS was not included as an OM input in the farm-gate budgets because the SOM reproducing effect of CG and CGS would have been calculated twice (in step 1 and step 2b), there is a risk of underestimating the SOM reproduction of CG (and CGS) because CGS might have a better SOM reproducing capacity than simply leaving CG on the field (Kolbe, 2013).

Furthermore, the program did not allow the adaptation of the SOM diminishing or reproducing effect of the crops in step 1. Regardless of the crops' yield (which varies between years), the program always assumes the same effect of the crops on the SOM content, but a higher or lower yield would clearly change the crop's effect on the SOM. Additionally, the program does not allow to note multiple crops for one field because the program would calculate both crops for the whole year. For example, in 2020 clover grass on KH1 was ploughed due to drought and broad bean was sown afterwards. This could not be noted in the program because both crops with its complete SOM effect would have been calculated. Instead a compromise had to be made and only clover grass was noted in the program. All these program's uncertainties and the decisions made (regarding e.g. CGS) to achieve the most realistic SOM budgets could distort the results. Additionally, the VDLUFA method of calculating SOM budgets is a very simple one with fixed values for SOM diminishing or reproducing parameters. Even though, Körschens (2010) argues that SOM budgets are the most reliable method at the time to estimate the SOM supply to the soil, he also recognizes that SOM budgets cannot predict changes in the SOM content but can merely estimate if the soil is adequately supplied with OM. Brock (2012) also concluded that precise changes in SOC content is not possible but trends of SOC changes can be predicted with SOM budgets which might allow to predict the impact of farming system on SOM content.

The VDLUFA method also does not take previous SOM contents, soil type (and therefore SOM turnover time), location or management of the soil (irrigation or cultivation) into account. These factors also influence the SOM budget which is why there is a need for further research and adaptation of the method (VDLUFA, 2014).

Chapter 1.3 focused on straw and its SOM-RC ignoring other OM materials such as compost or BD because Kleinhohenheim did not use these OM fertilizers. Only SOM budgets for the current management of Kleinhohenheim (straw was only OM input) were calculated and further SOM budget scenarios with compost or BD were not calculated because this would have exceeded the scope of this research. BD e.g. could have higher SOM-RC than forage left on the field (Erhart et al., 2014). Further research regarding the effect of compost, BD and other OM on the SOM budgets of Kleinhohenheim would be needed to develop strategies to further improve OM supply.

4.6. Soil organic matter budget results

When taking the previously (chapter 1.3) described long-term experiments into account it was unexpected to see positive SOM budgets because Kleinhohenheim did not import any external OM and only straw was used as OM inputs. On the other hand, VDLUFA (2014) had the highest SOM-RC for straw which indicated that a high straw input to the fields of Kleinhohenheim could lead to positive SOM budgets. Breitschuh and Gernand (2010) mentioned that farms with livestock had higher SOM budgets but also recognized that OFs had higher SOM budgets compared to conventional farms only because of their different crop rotation which contains more SOM reproducing legumes and the fertilization with straw in OA. The unexpected positive SOM budgets of this research might therefore also be explained by a crop rotation with a high share of legumes and a very high input of straw to the fields because almost all the straw at Kleinhohenheim was kept. This is how Kleinhohenheim could have positive SOM budgets despite being under stockless management without any external OM input.

The SOM field budgets had a similar overcalculation problem as the K field budgets because CGS was included in the calculations as OM input (step 2b) but step 1 already included the SOM reproduction effect of CG. So, the SOM reproduction effect in the SOM field budgets was calculated twice once for CG and once for CGS. The results of the average SOM field budget showed only a slight overestimation of CGS which might be explained by the input category chosen for CGS. As explained in chapter 4.5 CGS was noted as "Grünschnitt" as OM input which only has a very low SOM reproduction effect (16 kg SOM-C t^{-1}) which is why the OM did not influence the SOM field budget to a large extent. The average SOM field budget would have been even higher when CGS would have been noted with a SOM-RC of 115 kg SOM-C t^{-1}. It is uncertain how high the SOM-RC of CGS really is which is why this has to be researched before including it in SOM budget calculations.

The SOM KH8 field budgets showed similar results compared to the nutrient KH8 field budgets. KH8 showed the most negative nutrient and the lowest positive SOM field budget which might indicate that KH8 received too little inputs across the 7-year crop rotation.

The program rated the SOM budgets according to the evaluation system of "Direktzahlungen-Verpflichtungenverordnung (DirektZahlVerpflV)" (BGBl. Part I p. 2778 ff. from 4th of November 2004). This evaluation system is defined in the following with other evaluation systems even though it is not a legal requirement anymore. According to this evaluation system SOM budgets should be between – 75 kg C ha^{-1} year^{-1} and + 125 kg C ha^{-1} year^{-1}. Farms should not fall below – 75 kg C ha^{-1} year^{-1} because this would have negative effects on the soil fertility. But there are also other evaluation systems. The evaluation system of VDLUFA (2014) for example differentiates the SOM budget evaluation between conventional farms and OFs (Table 6). For conventional farms the SOM budget is optimal between – 75 kg C ha^{-1} year^{-1} and 100 kg C ha^{-1} year^{-1} while under – 200 kg C ha^{-1} year^{-1} is considered very low and over + 300 kg C ha^{-1} year^{-1} is considered very high. For OFs the SOM budget is optimal between 0 kg C ha^{-1} year^{-1} and up to + 300 kg C ha^{-1} year^{-1} while very low SOM budgets are the same as for conventional farms (under – 200 kg C ha^{-1} year^{-1}) but very high values are only reached when the SOM budget is over + 500 kg C ha^{-1} year^{-1} (Table 6). The same evaluation class entails higher SOM equivalent values for OFs compared to conventional farms because OA relies on a higher SOM content for optimal soil fertility which is why SOM budgets should be higher in OA (VDLUFA, 2014). Another evaluation system was given by Sächsische Landesanstalt für Landwirtschaft (2007) which specifies a much wider SOM equivalent range for the optimal SOM budget class (class C) for OA than for conventional agriculture (Figure 30). The optimal SOM budget ranges from – 75 kg C ha^{-1} year^{-1} to + 400 kg C ha^{-1} year^{-1} and only when the budget is over + 600 kg C ha^{-1} year^{-1} it is considered to be very high (class E).

Table 6: Evaluation system for SOM budgets grouped into classes after SOM equivalent ha^{-1} year^{-1}. The evaluation system is differentiated between conventional and organic farms. Source: VDLUFA (2014)

Class	Rating for conventional farms SOM equivalent kg C ha^{-1} year^{-1}	Rating for OFs SOM equivalent kg C ha^{-1} year^{-1}
A – very low	< - 200	< - 200
B – low	- 200 to - 76	- 200 to - 1
C – balanced	- 75 to 100	0 to 300
D – high	101 to 300	301 to 500
E – very high	> 300	> 500

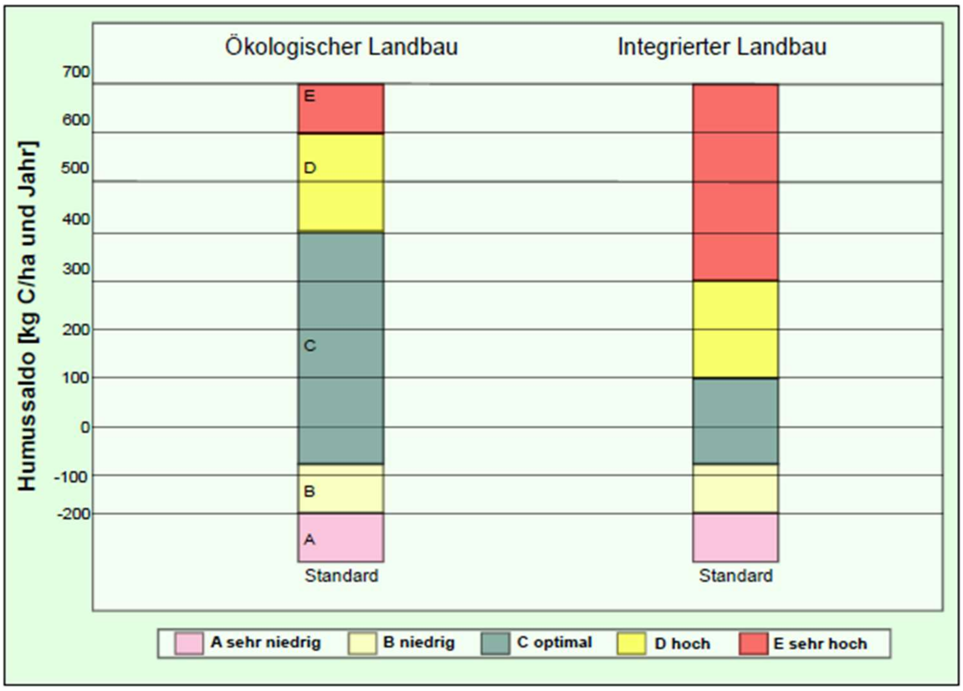


Figure 30: Evaluation system for SOM budgets evaluation according to Sächsische Landesanstalt für Landwirtschaft (2007).

Depending on the evaluation system the positive budget results of this research can be interpreted very differently. Using the evaluation system of "DirektZahlVerpflV" (BGBl. Part I p. 2778 ff. from 4th of November 2004) the farm-gate budgets of 2017, 2018 and 2022 would be rated as too high because they exceeded + 125 kg C ha^{-1} year^{-1} while farm-gate budgets of the other years would be rated as optimal. All field budgets (except KH8) would also be rated as too high. When VDLUFA (2014) is used to rate the budgets, all farm-gate and field budgets are in the optimal range between 0 kg C ha^{-1} year^{-1} and + 300 kg C ha^{-1} year^{-1} except KH3 which is slightly over + 300 kg C ha^{-1} year^{-1} (+ 306 kg C ha^{-1} year^{-1}). All the budgets (also

KH3 field budget) are rated as optimal when the evaluation system given by Sächsische Landesanstalt für Landwirtschaft (2007) is used.

Kolbe and Köhler (2008) found out that even the VDLUFA (2014) evaluation system class values are set too low for OA which results in budgets being rated as "very high" (class E) when they are actually just optimal. So, while the VDLUFA (2014) evaluation system would rate the average SOM farm-gate budget of this research (+ 141 kg C $\mathrm{ha}^{-1}\ \mathrm{year}^{-1}$) as being in the middle of the optimal range and the average SOM field budget (+ 204 kg C $\mathrm{ha}^{-1}\ \mathrm{year}^{-1}$) as being on the upper end of the optimal range Kolbe and Köhler (2008) suggest that both these budgets should actually be rated as being at the lower end of the optimal range. According to this evaluation system, Kleinhohenheim could aim at further increasing the SOM budgets to improve soil fertility and nutrient provision despite being already positive. Concerns about detrimental effects on the environment (e.g. nutrient leaching) through very high SOM budgets could not be confirmed by other OFs which had a very high SOM supply without experiencing the adverse environmental side effects (Kolbe and Köhler, 2008).

4.7. SOM budget results compared to soil analyses

SOM budgets calculated with the VDLUFA method are only useful for assessing the supply of OM to the soil and cannot give reliable insights into the change of SOM content over time (Körschens, 2010; VDLUFA, 2014). Even if SOM budgets from two different sites have similar results, the actual change in SOM content can differ between the sites depending on the soil's history and the site's circumstances (VDLUFA, 2014).

But Körschens (2010) also points out that two soil samples taken in two different years cannot accurately measure the change of SOM content because of the high variability of the $\mathrm{C}_{\mathrm{org}}$ contents in space and time. That is why, SOM budgets are still the best way to estimate if the supply of OM to the farm is sufficient (Körschens, 2010). On the other hand, the LfL (2019) argues that SOM budgets are not a reliable tool to determine the SOM content but instead suggests soil analyses every five to six years to determine the SOM content. These different approaches show that a contextualized assessment of the current SOM supply of Kleinhohenheim is only possible by comparing the budget results with soil analyses (from March 2021 and 2016). This way, it might be noticeable if SOM budgets are also transferred and reflected by the actual SOM content detected by the soil analyses.

The SOM contents vary with altitude (especially when the altitude is higher than 400 m above sea level (a.s.l.) there is a noticeable influence between the different altitudes on SOM content) and farm management strategy (Ebertseder et al., 2010). Besides all the different factors influencing SOM content one of the main factors is the soil type (Ebertseder et al., 2010; Sümmerer and Wiesmeier, 2023)

According to LfL (2019) the typical C_{org} content for loam or clay soils at < 350 m a.s.l. (Kleinhohenheim is 245 m a.s.l.) is approximately between 1 % and 2,16 %. After Körschens (2010) C_{org} has to be multiplied by 1,724 to get the total SOM content. This calculation results in an approximate SOM content between 1,724 % and 3,724 % for loam or clay soils. Körschens et al. (1998) gives values of 1-1,5 % of SOM in sandy soils and 3,5-4,4 % in clay soils. Another study from Sümmerer and Wiesmeier (2023) indicated a C_{org} content of 1,78 % for clayey loam soils ("schwach toniger Lehm" = t'L) which is equivalent to ~ 3,07 % SOM content. Ebertseder et al. (2010) group the soil types into three categories whereof "light" soils (sandy) have an average SOM content of 1,82 %, "middle" soils (loamy) have an average SOM content of 2,12 % and "heavy" soils (clayey) have an average SOM content of 2,42 %. Therefore, the clayey loam soil of Kleinhohenheim should have a SOM content between 2,12 % and 2,42 % according to Ebertseder et al. (2010).

The soil analyses of the Kleinhohenheim fields from 2021 shown in Table 3 revealed a SOM content between 1,6 % (KH6) and 2,65 % (KH4). The average of all fields is 2,04 %. According to LfL (2019) the average is within the range of an optimal SOM content but on the lower end. When assessing the average SOM content of Kleinhohenheim according to the optimal SOM content values given by Ebertseder et al. (2010), the average of 2,04 % is below the optimum. Sümmerer and Wiesmeier (2023) would categorize the average of 2,04 % as very low, far below the optimum of 3,07 %. So, according to these different sources the SOM content of the fields of Kleinhohenheim is either on the lower end or even below the optimal SOM content for clayey loam soils.

The SOM budget results on the other hand were positive and indicated an adequate supply with OM to the soil (chapter 3.4 and 3.5). The distinction between the positive budgets and the soil analyses with only low SOM contents might indicate, that the actual SOM turnover rate might be faster than anticipated by the program and even though the SOM budgets were positive the equilibrium of SOM content is around this measured value of 2,04 %. The SOM content could be further increased by applying more OM to the soil and a higher equilibrium would be established. This way Kleinhohenheim could not only increase its SOM content but its soil fertility overall.

Even though Körschens (2010; 2013) argued that it is not possible to assess the change of SOM content with just two soil analyses because the different results might be due to spatial or temporal variation, there is a reduction of almost 0,4 % average SOM content between 2016 and 2021. This large decrease might be overestimated due to the heterogeneity of the soil samples but in view of the fact, that Kleinhohenheim just recently (in 2010) changed management strategies towards a stockless farm management the differences of SOM contents between 2016 and 2021 might also indicate a trend of declining SOM content. After the management change the average SOM content of the farm might still establish a new SOM equilibrium. To maintain or restore the previously higher SOM content equilibrium a higher supply of OM would be needed.

Differences between observed SOM content and (with VDLUFA) calculated SOM budgets can indicate if the budget calculations correspond to the observed SOC content (Kolbe, 2010). Brock (2012) indicated that trends of SOM changes might be predictable with results of SOM budgets. But this was not the case in this research because SOM budgets were all positive and the SOM content in the soil declined from 2016 to 2021. Furthermore, Beuke (2006) found that SOM budgets calculated with the VDLUFA method underestimated the increase of $\mathrm{C_{org}}$ soil contents. If the observed SOC content is higher than the calculated budget this means that the budgets underestimate the SOC change (Kolbe, 2010). However, this research showed contrary results because it seemed like the positive SOM budgets overestimated the SOM content changes because instead of increasing or maintaining the SOM content the positive budgets even resulted in a SOM content decline. So, the SOM budgets did not seem to correspond to the observed SOM contents which could either be due to less accumulation or higher decomposition of SOM than calculated (Kolbe, 2010).

When Kolbe (2010) adapted the VDLUFA SOM equivalent values for the cultivation effects of the crops and OM to site-specific processes such as climate and soil-chemical influences the difference between observed SOM content and calculated SOM budgets was reduced by ~ 65 %. So, the results of SOM budgets could much more reliably give insights into the trend changes of SOM content when the SOM equivalent values were adapted.

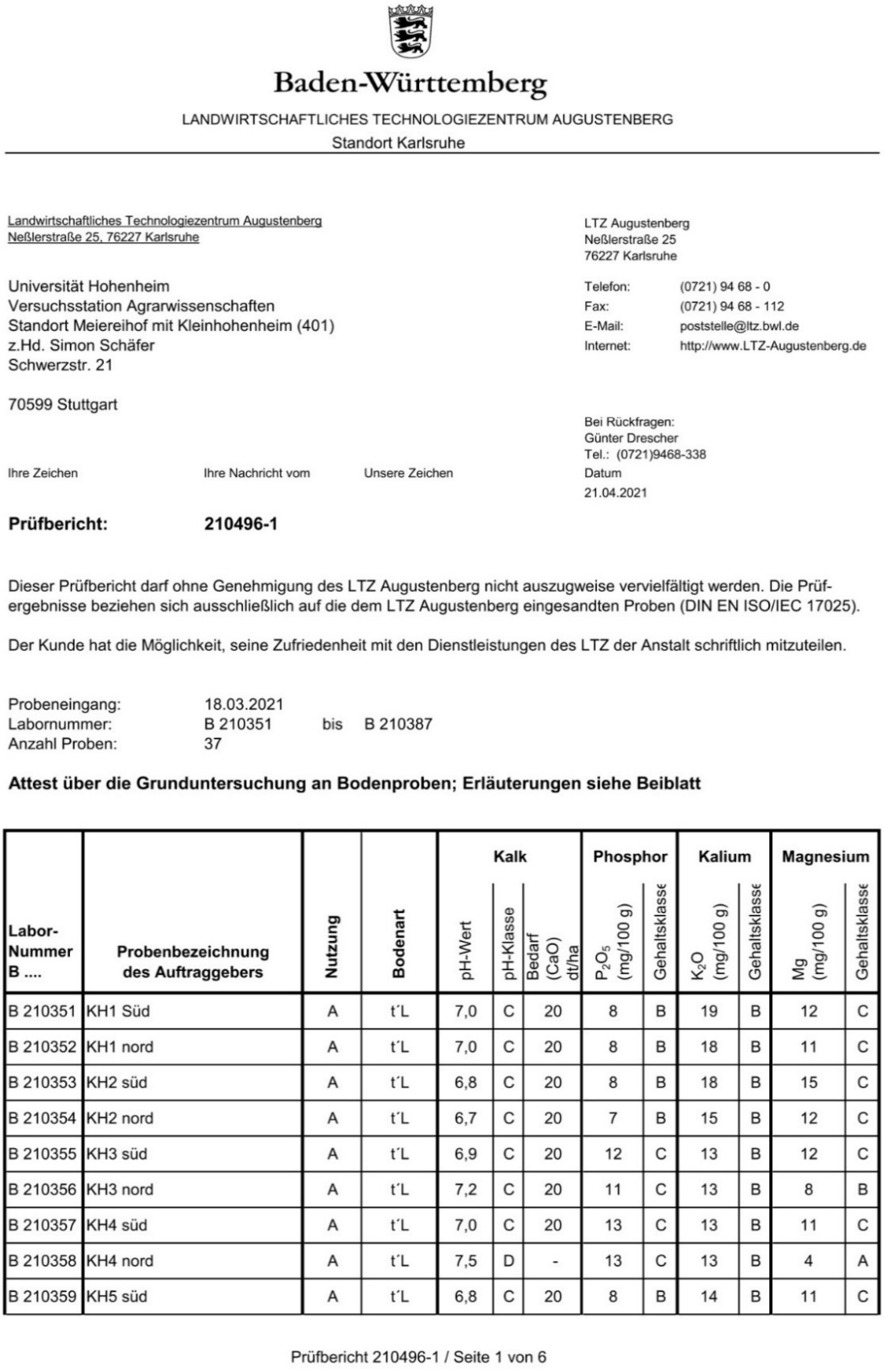
5. Conclusion

This thesis confirmed previous findings that arable stockless OFs have nutrient budget deficits for P and K because of a lack of external P and K fertilizer inputs. The research farm Kleinhohenheim (fields KH1 to KH8) did not import any external fertilizer (except carbolime) in the researched time period. This is why the nutrient farm-gate budgets for P and K were negative. The N farm-gate budget was positive because of the BNF through leguminous plants integrated in Kleinhohenheim's crop rotation. The average nutrient field budgets showed similar results, which means an average positive N field budget, negative P field budget and surprisingly positive K field budget due to unintended K inputs through CGS fertilization. Overall, it became clear, that the import of fertilizers is necessary to compensate the P and K losses. The nutrient farm-gate budgets calculated with three different fertilizer inputs (compost, BD and struvite) showed that BD and compost might be most suitable to compensate the nutrient losses because they increased both P and K budgets (while struvite only increased P budgets). Further research is needed to specify, which fertilizer characteristics are decisive for selecting the optimal fertilizer for Kleinhohenheim and how this fertilizer should be used.

Farm-gate and field SOM budgets were all positive indicating a sufficient supply of OM to the soil. Depending on the evaluation system with which the OM supply was evaluated the results can be rated as too high or optimal. Other literature indicated that a higher SOM budget could increase soil fertility for Kleinhohenheim. Soil analyses showed a decreasing SOM content (between 2016 and 2021) even though the OM supply was rated as sufficient by the Excel program. Therefore, OM supply could be even more increased to maintain the current SOM content or restore the previous SOM content. Further research and more monitoring of the SOM content should be done in a long-term experiment to assess if OM supply is sufficient or should be increased.

Appendix I

Soil nutrient analyses carried out by LTZ Augustenberg in March 2021. Received from Simon Schäfer.



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Ihre Zeichen
Ihre Nachricht vom
Unsere Zeichen
Datum
21.04.2021

Prüfbericht: 210496-1

Dieser Prüfbericht darf ohne Genehmigung des LTZ Augustenberg nicht auszugweise vervielfältigt werden. Die Prüfergebnisse beziehen sich ausschließlich auf die dem LTZ Augustenberg eingesandten Proben (DIN EN ISO/IEC 17025).

Der Kunde hat die Möglichkeit, seine Zufriedenheit mit den Dienstleistungen des LTZ der Anstalt schriftlich mitzuteilen.

Probeneingang: 18.03.2021
Labornummer: B 210351 bis B 210387
Anzahl Proben: 37

Attest über die Grunduntersuchung an Bodenproben; Erläuterungen siehe Beiblatt

Labor-Nummer B	Probenbezeichnung des Auftraggebers	Nutzung	Bodenart	Kalk			Phosphor		Kalium		Magnesium	
				pH-Wert	pH-Klasse	Bedarf (CaO) dt/ha	P_2O_5 (mg/100 g)	Gehaltsklasse	K_2O (mg/100 g)	Gehaltsklasse	Mg (mg/100 g)	Gehaltsklasse
B 210351	KH1 Süd	A	t´L	7,0	C	20	8	B	19	B	12	C
B 210352	KH1 nord	A	t´L	7,0	C	20	8	B	18	B	11	C
B 210353	KH2 süd	A	t´L	6,8	C	20	8	B	18	B	15	C
B 210354	KH2 nord	A	t´L	6,7	C	20	7	B	15	B	12	C
B 210355	KH3 süd	A	t´L	6,9	C	20	12	C	13	B	12	C
B 210356	KH3 nord	A	t´L	7,2	C	20	11	C	13	B	8	B
B 210357	KH4 süd	A	t´L	7,0	C	20	13	C	13	B	11	C
B 210358	KH4 nord	A	t´L	7,5	D	-	13	C	13	B	4	A
B 210359	KH5 süd	A	t´L	6,8	C	20	8	B	14	B	11	C

Labor-Nummer B	Probenbezeichnung des Auftraggebers	Nutzung	Bodenart	Kalk			Phosphor		Kalium		Magnesium	
				pH-Wert	pH-Klasse	Bedarf (CaO) dt/ha	P_2O_5 (mg/100 g)	Gehaltsklasse	K_2O (mg/100 g)	Gehaltsklasse	Mg (mg/100 g)	Gehaltsklasse
B 210360	KH5 nord	A	t´L	6,7	C	20	8	B	14	B	10	B
B 210361	KH6 süd	A	t´L	6,5	C	20	9	B	6	A	17	D
B 210362	KH6 nord	A	t´L	6,6	C	20	9	B	6	A	16	D
B 210363	KH7 süd	A	t´L	6,9	C	20	9	B	11	B	15	C
B 210364	KH7 nord	A	t´L	6,8	C	20	12	C	20	B	15	C
B 210365	KH8 süd	A	t´L	6,8	C	20	8	B	9	A	15	C
B 210366	KH8 nord	A	t´L	6,7	C	20	7	B	11	B	17	D

Bemerkungen:
Durchführung der Untersuchungen nach dem VDLUFA Methodenbuch Band I "Die Untersuchung von Böden".
Die Ergebnisse beziehen sich auf die angelieferten Proben.

Durch die DAkkS nach DIN EN ISO/IEC 17025 akkreditiertes Prüflaboratorium. Die Akkreditierung gilt nur für den in der Urkundenanlage D-PL-18996-02-00 aufgeführten Akkreditierungsumfang.

Prüfbericht 210496-1 / Seite 2 von 6

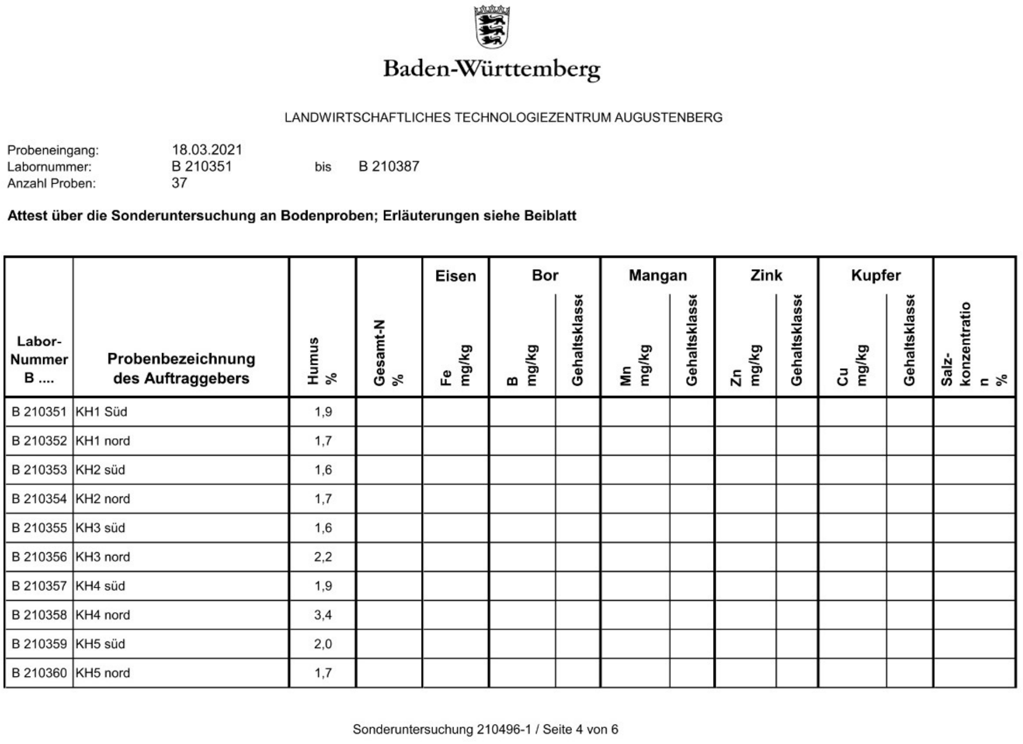
Es steht Ihnen jederzeit offen, Ihre Zufriedenheit oder auch Kritik über unsere Dienstleistungen dem LTZ Augustenberg schriftlich mitzuteilen.

LTZ Augustenberg, den 21.04.21

gez. Günter Drescher
Leiter SG Boden und Düngemittel Referat 22

Appendix II

SOM analyses carried out by LTZ Augustenberg in March 2021. Received from Simon Schäfer.



Baden-Württemberg

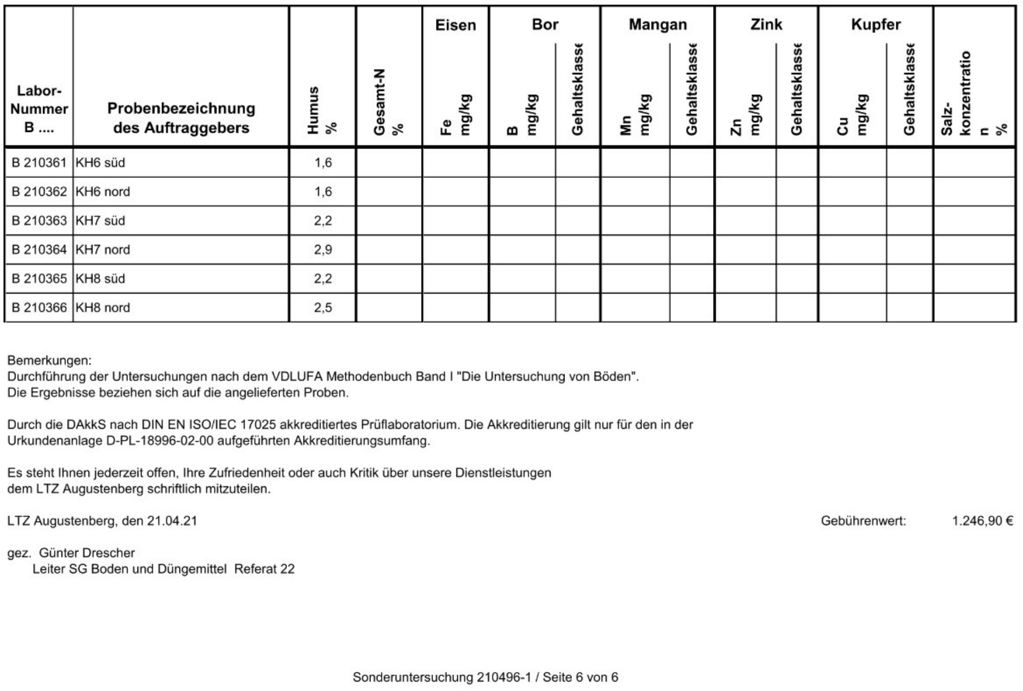
LANDWIRTSCHAFTLICHES TECHNOLOGIEZENTRUM AUGUSTENBERG

Probeneingang:	18.03.2021		
Labornummer:	B 210351	bis	B 210387
Anzahl Proben:	37		

Attest über die Sonderuntersuchung an Bodenproben; Erläuterungen siehe Beiblatt

Labor-Nummer B	Probenbezeichnung des Auftraggebers	Humus %	Gesamt-N %	Eisen	Bor		Mangan		Zink		Kupfer		Salz-konzentratio n %
				Fe mg/kg	B mg/kg	Gehaltsklass	Mn mg/kg	Gehaltsklass	Zn mg/kg	Gehaltsklass	Cu mg/kg	Gehaltsklass	
B 210351	KH1 Süd	1,9											
B 210352	KH1 nord	1,7											
B 210353	KH2 süd	1,6											
B 210354	KH2 nord	1,7											
B 210355	KH3 süd	1,6											
B 210356	KH3 nord	2,2											
B 210357	KH4 süd	1,9											
B 210358	KH4 nord	3,4											
B 210359	KH5 süd	2,0											
B 210360	KH5 nord	1,7											

Sonderuntersuchung 210496-1 / Seite 4 von 6



Labor-Nummer B	Probenbezeichnung des Auftraggebers	Humus %	Gesamt-N %	Eisen	Bor		Mangan		Zink		Kupfer		Salz-konzentratio n %
				Fe mg/kg	B mg/kg	Gehaltsklass	Mn mg/kg	Gehaltsklass	Zn mg/kg	Gehaltsklass	Cu mg/kg	Gehaltsklass	
B 210361	KH6 süd	1,6											
B 210362	KH6 nord	1,6											
B 210363	KH7 süd	2,2											
B 210364	KH7 nord	2,9											
B 210365	KH8 süd	2,2											
B 210366	KH8 nord	2,5											

Bemerkungen:
Durchführung der Untersuchungen nach dem VDLUFA Methodenbuch Band I "Die Untersuchung von Böden".
Die Ergebnisse beziehen sich auf die angelieferten Proben.

Durch die DAkkS nach DIN EN ISO/IEC 17025 akkreditiertes Prüflaboratorium. Die Akkreditierung gilt nur für den in der Urkundenanlage D-PL-18996-02-00 aufgeführten Akkreditierungsumfang.

Es steht Ihnen jederzeit offen, Ihre Zufriedenheit oder auch Kritik über unsere Dienstleistungen dem LTZ Augustenberg schriftlich mitzuteilen.

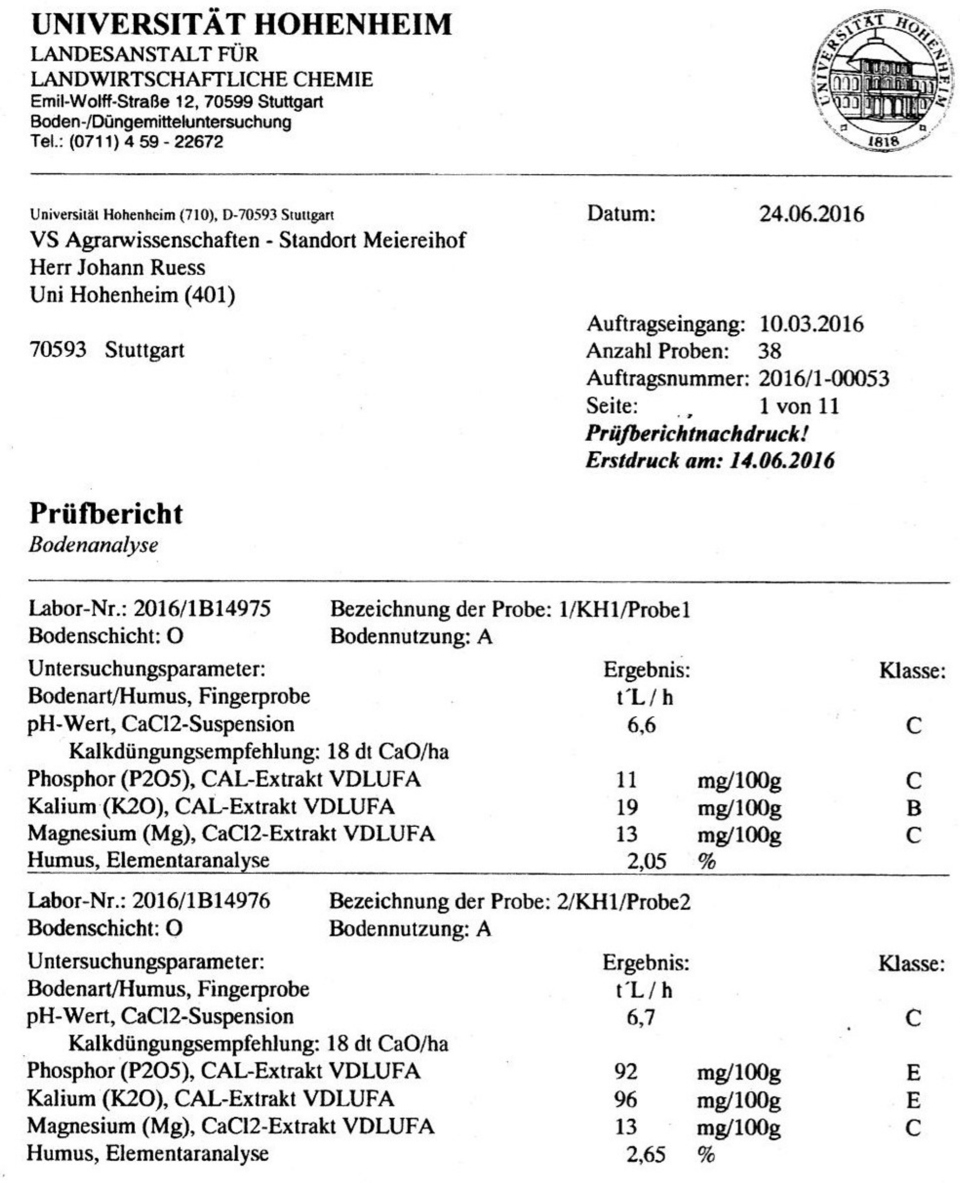
LTZ Augustenberg, den 21.04.21 Gebührenwert: 1.246,90 €

gez. Günter Drescher
Leiter SG Boden und Düngemittel Referat 22

Sonderuntersuchung 210496-1 / Seite 6 von 6

Appendix III

Nutrient and SOM analyses carried out by LTZ Augustenberg in March 2016. Received from Simon Schäfer.



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Datum: 24.06.2016

Auftragseingang: 10.03.2016
Anzahl Proben: 38
Auftragsnummer: 2016/1-00053
Seite: 1 von 11
Prüfberichtnachdruck!
Erstdruck am: 14.06.2016

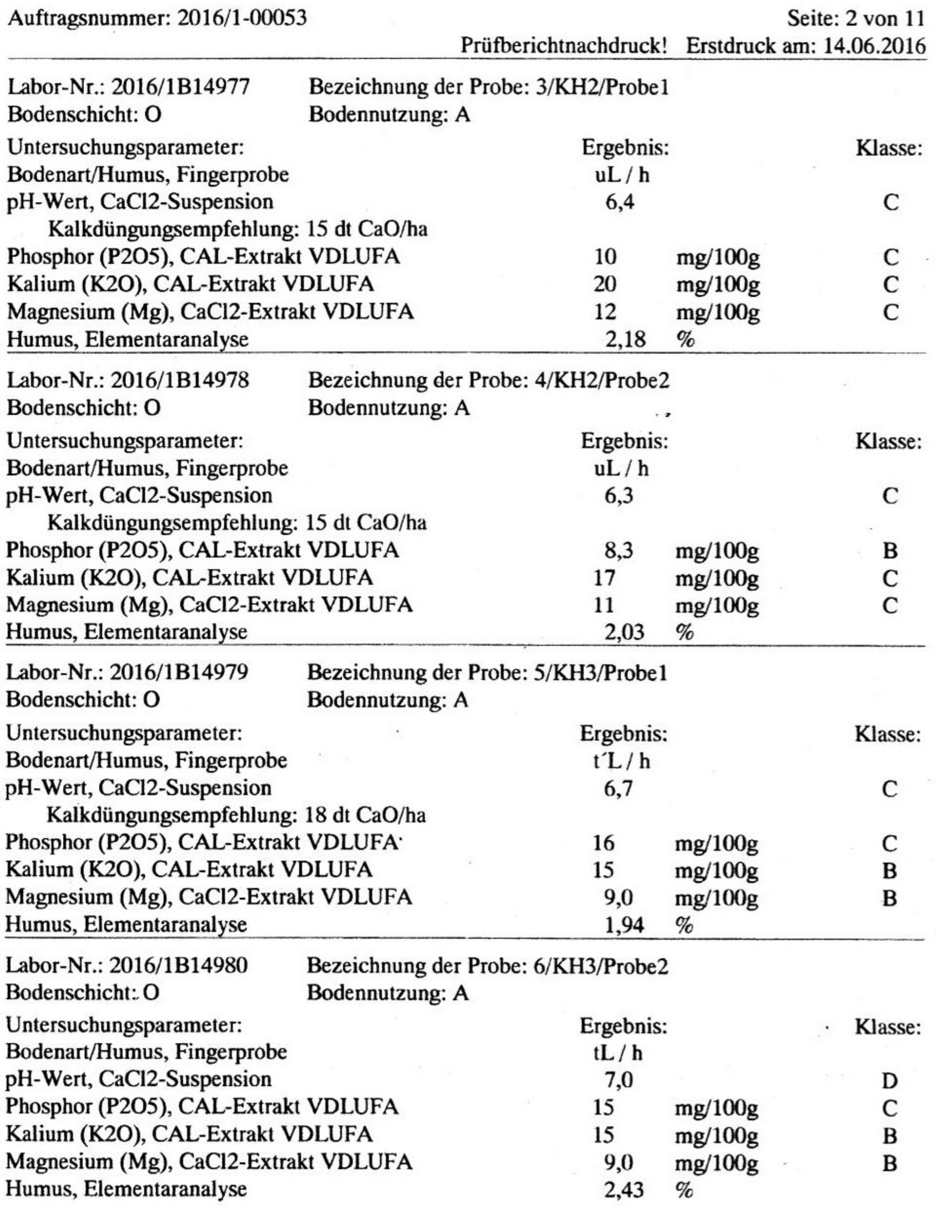
Prüfbericht
Bodenanalyse

Labor-Nr.: 2016/1B14975 Bezeichnung der Probe: 1/KH1/Probe1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t´L / h		
pH-Wert, CaCl2-Suspension	6,6		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	11	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	19	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	13	mg/100g	C
Humus, Elementaranalyse	2,05	%	

Labor-Nr.: 2016/1B14976 Bezeichnung der Probe: 2/KH1/Probe2
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t´L / h		
pH-Wert, CaCl2-Suspension	6,7		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	92	mg/100g	E
Kalium (K2O), CAL-Extrakt VDLUFA	96	mg/100g	E
Magnesium (Mg), CaCl2-Extrakt VDLUFA	13	mg/100g	C
Humus, Elementaranalyse	2,65	%	



Labor-Nr.: 2016/1B14977 Bezeichnung der Probe: 3/KH2/Probe1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	uL / h		
pH-Wert, CaCl2-Suspension	6,4		C
Kalkdüngungsempfehlung: 15 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	10	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	20	mg/100g	C
Magnesium (Mg), CaCl2-Extrakt VDLUFA	12	mg/100g	C
Humus, Elementaranalyse	2,18	%	

Labor-Nr.: 2016/1B14978 Bezeichnung der Probe: 4/KH2/Probe2
Bodenschicht: O Bodennutzung: A

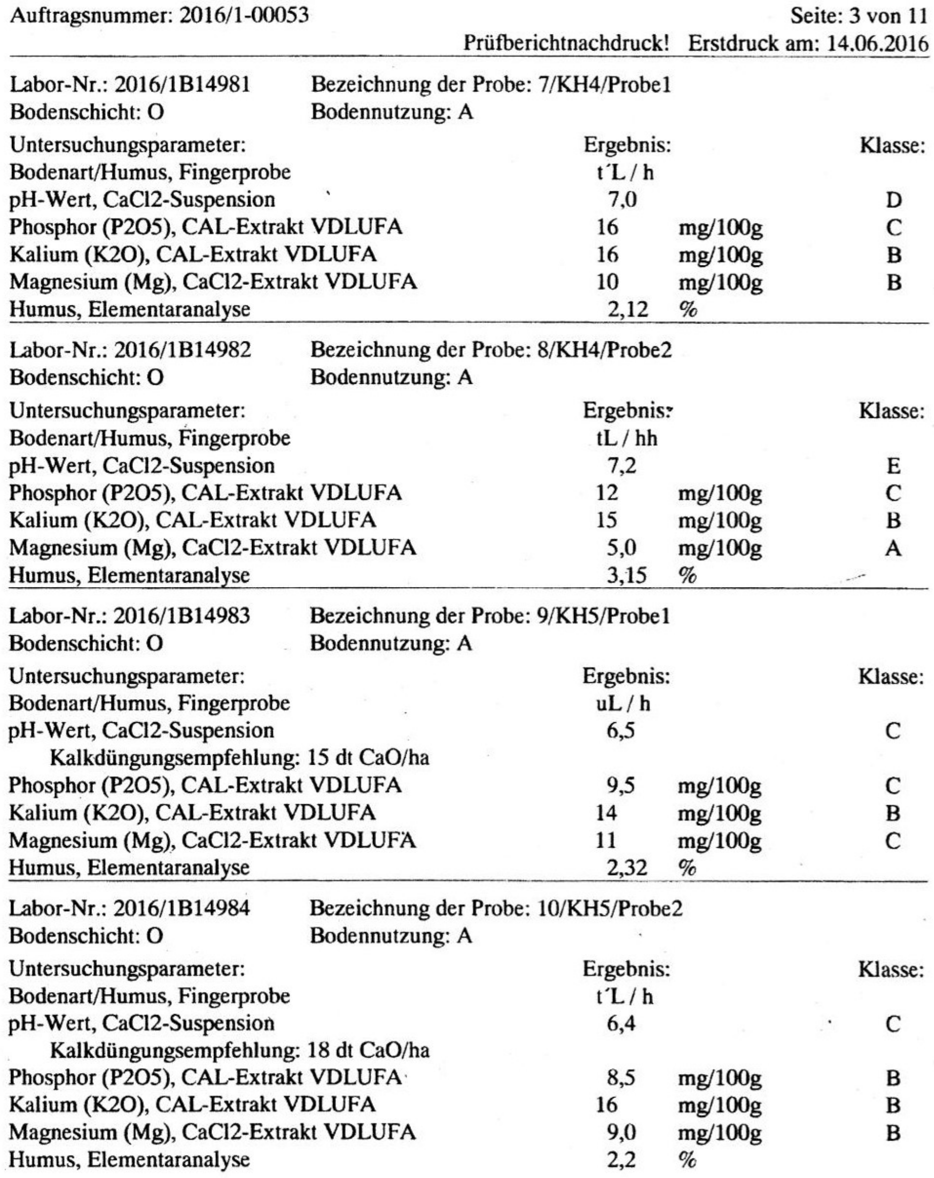
Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	uL / h		
pH-Wert, CaCl2-Suspension	6,3		C
Kalkdüngungsempfehlung: 15 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	8,3	mg/100g	B
Kalium (K2O), CAL-Extrakt VDLUFA	17	mg/100g	C
Magnesium (Mg), CaCl2-Extrakt VDLUFA	11	mg/100g	C
Humus, Elementaranalyse	2,03	%	

Labor-Nr.: 2016/1B14979 Bezeichnung der Probe: 5/KH3/Probe1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t´L / h		
pH-Wert, CaCl2-Suspension	6,7		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	16	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	15	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	9,0	mg/100g	B
Humus, Elementaranalyse	1,94	%	

Labor-Nr.: 2016/1B14980 Bezeichnung der Probe: 6/KH3/Probe2
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	tL / h		
pH-Wert, CaCl2-Suspension	7,0		D
Phosphor (P2O5), CAL-Extrakt VDLUFA	15	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	15	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	9,0	mg/100g	B
Humus, Elementaranalyse	2,43	%	



Labor-Nr.: 2016/1B14981 Bezeichnung der Probe: 7/KH4/Probe1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t'L / h		
pH-Wert, CaCl2-Suspension	7,0		D
Phosphor (P2O5), CAL-Extrakt VDLUFA	16	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	16	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	10	mg/100g	B
Humus, Elementaranalyse	2,12	%	

Labor-Nr.: 2016/1B14982 Bezeichnung der Probe: 8/KH4/Probe2
Bodenschicht: O Bodennutzung: A

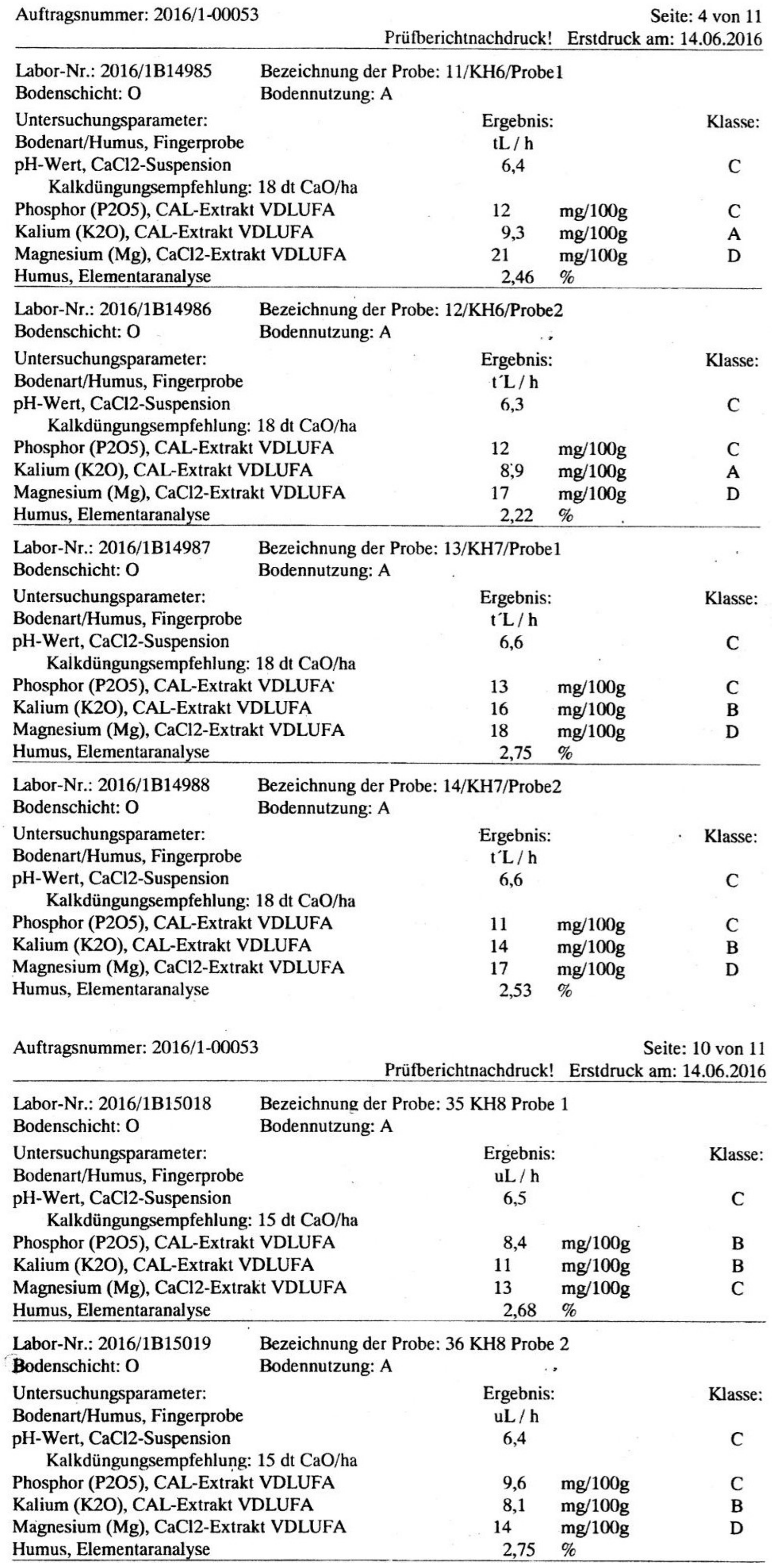
Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	tL / hh		
pH-Wert, CaCl2-Suspension	7,2		E
Phosphor (P2O5), CAL-Extrakt VDLUFA	12	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	15	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	5,0	mg/100g	A
Humus, Elementaranalyse	3,15	%	

Labor-Nr.: 2016/1B14983 Bezeichnung der Probe: 9/KH5/Probe1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	uL / h		
pH-Wert, CaCl2-Suspension	6,5		C
Kalkdüngungsempfehlung: 15 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	9,5	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	14	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	11	mg/100g	C
Humus, Elementaranalyse	2,32	%	

Labor-Nr.: 2016/1B14984 Bezeichnung der Probe: 10/KH5/Probe2
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t'L / h		
pH-Wert, CaCl2-Suspension	6,4		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	8,5	mg/100g	B
Kalium (K2O), CAL-Extrakt VDLUFA	16	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	9,0	mg/100g	B
Humus, Elementaranalyse	2,2	%	



Auftragsnummer: 2016/1-00053 Seite: 4 von 11
Prüfberichtnachdruck! Erstdruck am: 14.06.2016

Labor-Nr.: 2016/1B14985 Bezeichnung der Probe: 11/KH6/Probe1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	tL / h		
pH-Wert, CaCl2-Suspension	6,4		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	12	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	9,3	mg/100g	A
Magnesium (Mg), CaCl2-Extrakt VDLUFA	21	mg/100g	D
Humus, Elementaranalyse	2,46	%	

Labor-Nr.: 2016/1B14986 Bezeichnung der Probe: 12/KH6/Probe2
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t´L / h		
pH-Wert, CaCl2-Suspension	6,3		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	12	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	8,9	mg/100g	A
Magnesium (Mg), CaCl2-Extrakt VDLUFA	17	mg/100g	D
Humus, Elementaranalyse	2,22	%	

Labor-Nr.: 2016/1B14987 Bezeichnung der Probe: 13/KH7/Probe1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t´L / h		
pH-Wert, CaCl2-Suspension	6,6		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	13	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	16	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	18	mg/100g	D
Humus, Elementaranalyse	2,75	%	

Labor-Nr.: 2016/1B14988 Bezeichnung der Probe: 14/KH7/Probe2
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	t´L / h		
pH-Wert, CaCl2-Suspension	6,6		C
Kalkdüngungsempfehlung: 18 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	11	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	14	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	17	mg/100g	D
Humus, Elementaranalyse	2,53	%	

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Labor-Nr.: 2016/1B15018 Bezeichnung der Probe: 35 KH8 Probe 1
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	uL / h		
pH-Wert, CaCl2-Suspension	6,5		C
Kalkdüngungsempfehlung: 15 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	8,4	mg/100g	B
Kalium (K2O), CAL-Extrakt VDLUFA	11	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	13	mg/100g	C
Humus, Elementaranalyse	2,68	%	

Labor-Nr.: 2016/1B15019 Bezeichnung der Probe: 36 KH8 Probe 2
Bodenschicht: O Bodennutzung: A

Untersuchungsparameter:	Ergebnis:		Klasse:
Bodenart/Humus, Fingerprobe	uL / h		
pH-Wert, CaCl2-Suspension	6,4		C
Kalkdüngungsempfehlung: 15 dt CaO/ha			
Phosphor (P2O5), CAL-Extrakt VDLUFA	9,6	mg/100g	C
Kalium (K2O), CAL-Extrakt VDLUFA	8,1	mg/100g	B
Magnesium (Mg), CaCl2-Extrakt VDLUFA	14	mg/100g	D
Humus, Elementaranalyse	2,75	%	

Appendix IV

Access to excel files of nutrient and SOM budget calculations and the corresponding data:

https://bwsyncandshare.kit.edu/s/GrysoaMTGxHbwot

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Mitteilung der Kommission an das Europäische Parlament, den Rat, den Europäischen Wirtschafts- und Sozialausschuss und den Ausschuss der Regionen über enen Aktionsplan zur Förderung der ökologischen/biologischen Produktion (EU Commission COM/2021/141 final/2)

Commission Implementing Regulation (EU) 2023/121 of 17 January 2023 amending and correcting Implementing Regulation (EU) 2021/1165 authorising certain products and substances for use in organic production and establishing their lists (OJEU L16 from 16th February 2023)

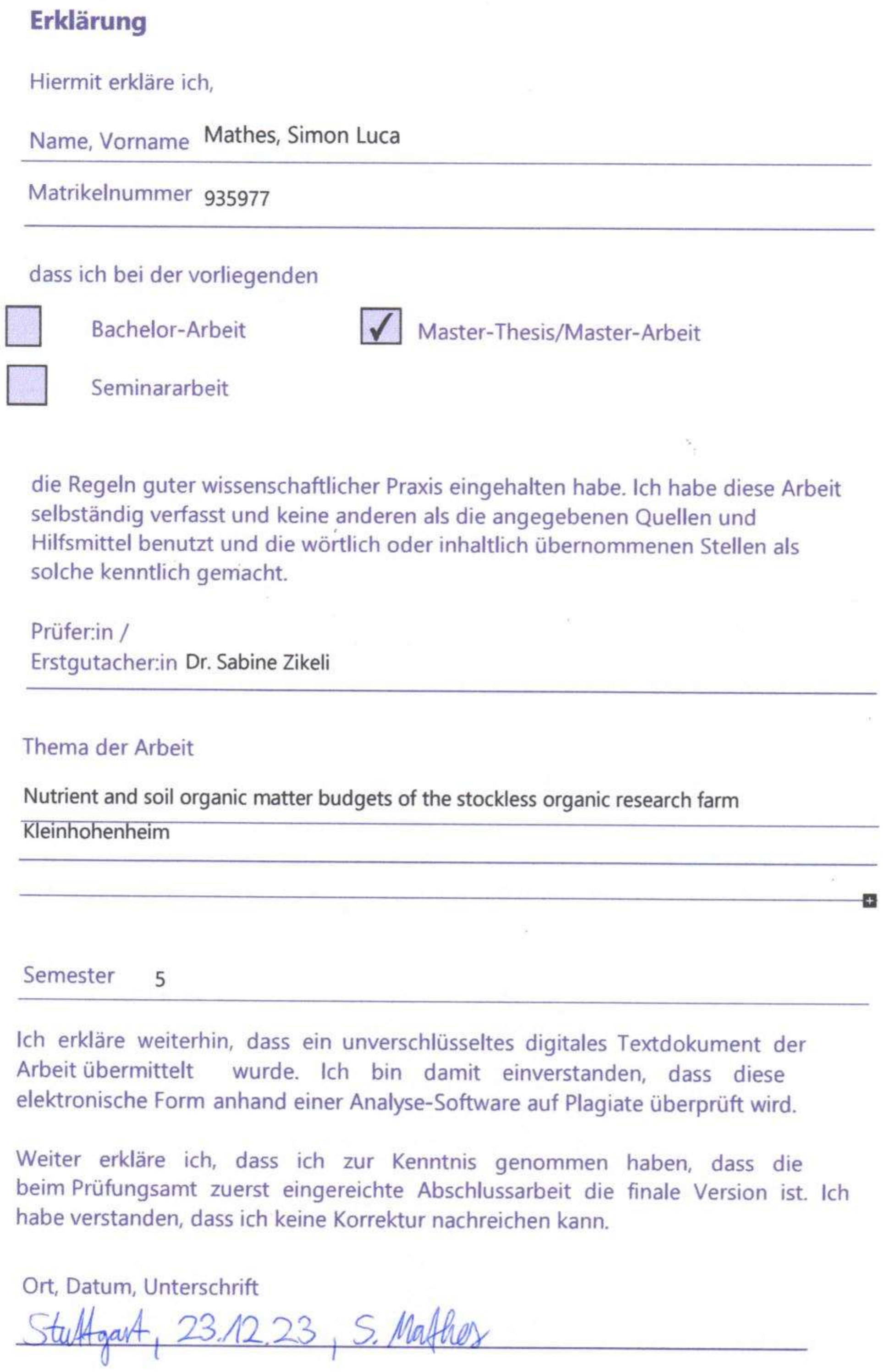
Düngeverordnung (DüV) vom 26. Mai 2017 (BGBl. I S. 1305), die zuletzt durch Artikel 97 des Gesetzes vom 10. August 2021 (BGBl. I S. 3436) geändert worden ist.

Bioabfallverordnung (BioAbfV) in der Fassung der Bekanntmachung vom 4. April 2013 (BGBl. I S. 658), die zuletzt durch Artikel 1 der Verordnung vom 28. April 2022 (BGBl. I S. 700; 2023 I Nr. 153) geändert worden ist.

Bundes-Bodenschutzgesetz (BBodSchG) vom 17. März 1998 (BGBl. I S. 502), das zuletzt durch Artikel 7 des Gesetzes vom 25. Februar 2021 (BGBl. I S. 306) geändert worden ist.

Direktzahlungen-Verpflichtungenverordnung (DirektZahlVerpflV) „Verordnung über die Grundsätze der Erhaltung landwirtschaftlicher Flächen in einem guten landwirtschaftlichen und ökologischen Zustand“ (BGBl. Part I p. 2778 ff. from 4th of November 2004)

Declaration of originality



Erklärung

Hiermit erkläre ich,

Name, Vorname Mathes, Simon Luca

Matrikelnummer 935977

dass ich bei der vorliegenden

☐ Bachelor-Arbeit ☑ Master-Thesis/Master-Arbeit

☐ Seminararbeit

die Regeln guter wissenschaftlicher Praxis eingehalten habe. Ich habe diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt und die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht.

Prüfer:in /
Erstgutacher:in Dr. Sabine Zikeli

Thema der Arbeit

Nutrient and soil organic matter budgets of the stockless organic research farm Kleinhohenheim

Semester 5

Ich erkläre weiterhin, dass ein unverschlüsseltes digitales Textdokument der Arbeit übermittelt wurde. Ich bin damit einverstanden, dass diese elektronische Form anhand einer Analyse-Software auf Plagiate überprüft wird.

Weiter erkläre ich, dass ich zur Kenntnis genommen haben, dass die beim Prüfungsamt zuerst eingereichte Abschlussarbeit die finale Version ist. Ich habe verstanden, dass ich keine Korrektur nachreichen kann.

Ort, Datum, Unterschrift

Stuttgart, 23.12.23, S. Mathes