



Intermediate wheatgrass (Kernza™) as a pre-crop for beetroot and carrot

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Independent project in Biology • 30 credits
Swedish University of Agricultural Sciences, SLU
Faculty of Landscape Architecture, Horticulture and Crop Production
Science
Horticultural Science Programme
Alnarp 2026

Intermediate wheatgrass (Kernza™) as a pre-crop for beetroot and carrot

Intermediate wheatgrass (Kernza™) som förgröda åt rödbeta och morot

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Credits:	30 credits
Level:	Second cycle, A2E
Course title:	Independent Project in Biology, A2E
Course code:	EX0856
Programme/education:	Horticultural Science Programme
Course coordinating dept:	Department of Plant Breeding
Place of publication:	Alnarp
Year of publication:	2026
Copyright:	All featured images are used with permission from the copyright owner.
Keywords:	Kernza, intermediate wheatgrass, perennial, crop rotation, microorganisms, nutrient cycling

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Abstract

This study is laid out with the background of some of today's biggest societal needs: climate change resilient agricultural systems, and food chains less reliant on fossil fuels and more irrepressible to political change. The interest for perennial incorporation into crop cycles is due to their dual use, in that they often can be harvested both for seed and straw. However, knowledge gaps concerning how perennial grasses function as pre-crops need filling before such crops can be fully utilized. Through a study design using carrot and beetroot as subsequent crops to Kernza™ (cropped for six consecutive years) comparison of pre-crop qualities with a conventional annual cereal crop cycle was made. Looking at soil parameters such as water content and organic matter content, where measurements were significantly higher for the perennial treatment with Kernza™, pre-crop qualities seem high. However, the findings of this field study also show a significantly lower harvest weight of subsequent crops, compared with the harvest of subsequent crops following conventional cereal crops (referred to as the annual treatment). Bulk density and pH do not differ significantly between the treatments, although respiration is significantly higher in the perennial treatment. These results indicate that the soil processes following the use of perennial crops, and the effects of management such as termination timing and depth of tillage, have intricate ways of influencing subsequent crops, most likely in the establishment phase as well as harvest weight. Looking at the results of this field study, together with the literature study, it is still clear that Kernza™ needs more research focus as a pre-crop to be fully utilized in crop circles that include perennial cereals as well as annual crops for direct human consumption.

Swedish abstract

Denna studie tar sin utgångspunkt i några av dagens största samhällsbehov: jordbrukssystem som är resilienta under ett förändrat klimat och livsmedelskedjor som är mindre känsliga för politiska förändringar och mindre beroende av fossila bränslen. Intresset för att integrera perenner i växtrotationer beror på deras mångfaldiga användningsområden - de kan ofta skördas för både frö och halm. Det finns dock kunskapsluckor om hur perenna gräs, såsom Kernza™, fungerar som förgrödor. Dessa luckor måste fyllas innan sådana grödor kan utnyttjas till fullo. Genom den här studien, där morötter och rödbetor odlas som efterföljande grödor efter Kernza™ (odlad under sex år i rad), jämfördes förgrödornas egenskaper med en konventionell växtföljd bestående av ettåriga spannmålsgrödor. Sett till jordparametrar som vattenhalt och halt av organiskt material, där mätningarna var betydligt högre för den perenna behandlingen med Kernza™, verkar förgrödans egenskaper vara goda. Resultaten av denna fältstudie visar dock också en betydligt lägre skördevikt jämfört med de grödor som odlats efter annuella spannmålsgrödor. Bulkdensitet och pH skiljer sig inte signifikant mellan behandlingarna, men respirationen är signifikant högre i den perenna behandlingen. Dessa resultat indikerar att markprocesser efter inkorporering av perenna grödor och även effekter av skötselåtgärder (såsom tidpunkt för slutplöjning och även plöjningsdjup) har komplex påverkan på efterföljande grödor, troligen både under etableringsfasen och senare på skördevikten. Med tanke på resultaten från denna fältstudie, tillsammans med litteraturstudien, är det fortfarande tydligt att Kernza™ behöver mer forskningsfokus som förgröda för att kunna utnyttjas fullt ut i växtföljder som inkluderar perenna spannmål samt ettåriga grödor ämnade för direktkonsumtion.

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Introduction

Swedish context

Agricultural land in Sweden is most widely used for cereal cropping, where wheat production is largest, followed by ley production. Consecutively, we have production of rape seed, turnip rape, potato, and sugar beet (Jordbruksverket 2021); agricultural products that are largely intended for different types of processing (fat, oil, sugar, and liquor crops). The cropping systems for cereals are one of the most disturbed ecosystems we have today, when considering the scope, frequency of tillage and intensity (Crews et al. 2018a). This is why it is important that we not only consider replacing the fat, oil, sugar, and liquor crops that are largely incorporated in grain cropping systems, but also replacing the type of grain we cultivate with species that are less dependent on continuous re-sowing, and hence soil disturbing activities.

Background

The vulnerability of our current food production systems has been a central topic in Europe and in Sweden since the start of the COVID-19 pandemic in 2019, and due to Russia's full-scale invasion of Ukraine in 2022, it has remained in the centre of political discussions and debates within the civil society, often with special attention to preparedness (Regeringskansliet 2022; Landets Fria Tidning 2022). The political agendas pervading Sweden's national food strategy focus highly on increased exports and competitiveness on an international market (Regeringskansliet 2023); modes of production and distribution adjusted to largely industrialized production units. A high dependency on fossil fuels, as well as high use of chemical fertilizers and pesticides compared to peasant agriculture, increases the vulnerability of the industrialized agricultural production model. It also creates production systems in which the revenue from farms do not return to the farmer, offering a liveable salary, but rather to the processing industry and the producers of agricultural machinery and inputs (Crews et al. 2018a). Even in the organic sector, the phenomena of 'conventionalization' leads to a similar dependency and therefore weakens otherwise positive correlations between organic production systems and agrobiodiversity, for example. Production systems that are oriented towards local consumers rather than industries, and that produce food for direct distribution rather than processing, are better able to safeguard and increase agrobiodiversity (Rover et al. 2020). To alleviate the pressure put on food production and food supply chains, both nationally and within Europe, it is necessary to look at agricultural models that incorporate agroecological principles. This includes shorter supply chains, and cultivation of crops intended for direct human consumption.

Perennials and root vegetables in crop rotations

Processing factories are seldom certified for organic production since the consumer demand for processed, organic products is generally lower compared to the demand for fresh organic produce (Robson et al. 2002); therefore, it is easier to motivate organic cultivation for crops intended for direct human consumption. Even leaving the industrial inclination or capacity to meet demands for processed organic products aside, it is important to consider the social, political and health

consequences of processed foods. Monteiro et al. (2017) discuss these, as well as environmental consequences, and their relationship to processed or ultra-processed food products. One of the issues when replacing fresh or minimally processed foods with heavily refined products is the rearrangement of local and global food culture. Food culture is transformed and aligned with the interests of transnational corporations as opposed to people's nutritional needs and traditional food cultures. Such a transformation is demonstrably correlated with disease, health complications, and increased negative environmental impacts (Monteiro et al. 2017). As a strategy for mitigating the accumulation of power of big agriculture and transnational corporations, food sovereignty is being promoted; Anderson et al. (2018) describes food sovereignty as "... a radical and political project of food system transformation that emphasizes the democratization of agriculture and food, rights of food producers and autonomy from powerful external actors (e.g., agribusiness, political elite)" (Anderson et al. 2018:1). The cultivation of crops that are socially acceptable and suitable for direct consumption alleviates allocation of power to industries and transnational corporations, allows for local food culture and a strengthening of the relationship between consumers and producers of food, all aligning with the goals of food sovereignty. In a study carried out by Andersson et al. (2018:1), based on research conducted in collaboration with the international peasant movement La Via Campesina, it is evident that to achieve food sovereignty, university-based research must also realign with societal and local needs, in the same way as is needed in food production systems. Beetroots and carrots have been chosen as subsequent crops in this study due to their readiness for direct consumption as well as their suitability for longer-term storage.

One of the biggest challenges of agricultural production systems today is to resist soil degradation while feeding a growing global population (Crews et al. 2022). One function that is lost in the conversion from natural ecosystems to arable land is the adept cycling of nitrogen, which is mainly due to the removal of perennials. While extending crop duration in fields to minimize soil compaction and erosion by avoiding tillage, leaning less on fossil fuels and chemical inputs will also allow us to lessen the negative environmental impact of food production systems. Additionally, longer crop durations can create tighter nutrient cycles, and better utilize resources such as water and sunlight. Perennial grains do not require annual tillage and therefore soil disturbing activities are minimized (Chapman et al. 2022); through deep rooting, they also retain greater amounts of nutrients and prevent leaching. Crews et al. (2018b) discuss whether perennials are a main part of the agricultural future and bring up several aspects of socio-economic importance. They are stating that the well-known beneficial effects of perennials on soil motivate studies of the role and placement of perennials within crop rotations. Studies such as these are also motivated by our increased need for climate change mitigation strategies; perennials provide both soil coverage over a longer time-period compared to annual crops and provide higher inputs of carbon through larger roots and continuous root-turnover.

Aim & research question

The goal is to investigate what qualities Kernza has as a precrop for beetroot and carrot. To achieve this goal the study includes the establishment of a study area

within the Lönstorp research fields. Here, the effects of Kernza as a precrop for beet and carrot are studied and compared to the precrop traits of a crop rotation with exclusively annual crops. A societal goal with this project is to illustrate the production of crops that can be used for direct consumption rather than for industrial processing and refining, as is most common for crops included in cereal production systems. This aim is pursued by the donation of the harvest of beets and carrots to local restaurants.

Materials & methods

The project consists of literature studies as well as field measurements. The literature study aims to investigate what is already known about the beneficial and challenging aspects of including Kernza in a crop rotation in temperate climates. Field studies complement the literature study by the following methods:

1. Estimating soil compactness in the fields where beetroots and carrots are grown following Kernza (referred to as treatment P or the perennial treatment) and the field with annual crop rotation (referred to as treatment A or the annual treatment), respectively, was done twice by measuring soil bulk density, once in May before establishment of the subsequent crops, and one additional time in September.
2. An evaluation of potential regrowth (as well as self-seeding) of Kernza during the growing season (July) by visual inspections.
3. Measuring the abundance of weeds in cultivated beetroot and carrot during July by visually grading the percentage cover of each species in each observed plot (12 plots at this time). Weed abundance is also measured by the dry weight of weeds (g).
4. The quantity and quality of beetroot and carrot harvest by visual assessment and size classification made by imitating local standards for small-scale and organic production (see [Appendix 1](#) for details regarding the classification model), was done on September 21st.
5. Quantifying precrop quality based on the measurement results of the following indicators: Respiration, pH-value, soil water content (WC, %) and organic matter content (LOI, %). These measurements were also made twice; pH and bulk density in May and September, and respiration, water content as well as organic matter content was measured in July and September.
6. To detect significant differences in these measurements, analysis of variance (ANOVA) with Tukey's Post-hoc test at the significance level of $p < 0.05$ was performed using the MiniTab software. To facilitate interpretation of influence of soil characteristics on crop performance, Spearman correlation tests were run for soil pH, water content, loss on ignition, bulk density, and respiration, against the quantitative yield parameters.

Limitations

The scope of the study will cover temperate regions essentially. The study will use the fields at Lönnstorp (latitude 55.67°N 13.11°E) as the area for field research. The results will thus be applicable to areas with similar growing conditions.

Results

Literature study

Beets, carrots and perennials

Using Kernza in crop rotations can be motivated by several points; Zimbric et al. (2020) call Kernza a dual-use crop and highlight the benefit of being able to harvest both grain and straw during each crop cycle. Kernza can therefore be used to provide fodder for livestock as well as food for people, increasing potential income for producers. Additionally, natural ecosystems are more efficient at providing ecosystem services, as well as utilizing water and nutrients that enter these systems (Crews et al. 2018a). The link between perennialism and higher resource utilization also contributes to building the soil up; perennial systems maintain higher levels of soil nitrogen and carbon compared to annual wheat fields (DuPont et al. 2014). Crews et al. (2018a) state that annual crops exploit rather than build soil, and that such agricultural systems are contributing heavily to soil erosion. In a field experiment performed by Chahal et al. (2021) in Ontario, Canada, two long-term field trials established 1980 and 1995 respectively were used to estimate crop yield in relation to different types of land management. A positive correlation was found between an increased amount of organic carbon in the soil and higher yields of winter wheat, corn and soybean for treatments including cover crops and perennials in the rotation. The benefits of no-till management on soil microbial activity were also confirmed. Above this, perennial systems can successfully uphold diversity among pollinators, herbivores and detritus feeders (DuPont et al. 2014).

The efficiency of providing ecosystem services is higher in stable, natural ecosystems, where perennials dominate (Crews et al. 2018b). Managing agricultural production in a way that approximates these systems may be our best option when it comes to soil health and protection. The intermediate wheatgrass Kernza is a commercial crop, a food crop, as well as a grass and cover crop, due to its perennialism. Possibilities that this type of multifaceted crop holds can be investigated in a rotation with beetroots and carrots.

Root-systems create biopores which can be utilized by the following crops in the plant rotation (Lucas et al. 2019; Han et al. 2016), and considering the larger root-systems of perennials, a higher number of biopores are created (Han et al. 2021). The duration of these biopores vary with the coarseness and decomposition rate of the roots, diversifying pore-access for establishing and growing roots. Both beets and carrots need porous soil and are well suited following crops with deep and coarse root systems (Ögren & Jonsson, 2015). Yet, when Kernza is grown for both seeds and above-ground biomass, repeated forage harvests might risk eventually compacting the ground, since it is not continuously ploughed and thereby uncompacted (Glab 2007). When carrot is used as a subsequent crop, soil activities

causing heavy soil pressure should be avoided during the later part of the previous growing season and early spring before sowing. If however, soil preparation activities hasten the heating up of the soil in spring time, and maintain a porous soil structure, it is best suited for carrots (Ögren & Jonsson, 2015). Growing crops with large root systems might mitigate the consequences of compacted soil. In a study by Materechera et al. (1992) it was found that the roots of plants growing in compacted subsoil gained larger diameters, considered due to compaction pressure. Perkons et al. (2014) conducted a field study where annual winter wheat was grown after two consecutive years of the perennial chicory (*Cichorium intybus* L., a fodder crop with a large taproot). Compared to pre-crops with fibrous root systems, the study found that roots of winter wheat would increase its root length densities following the cultivation of chicory. Materechera et al. (1992) look into how the root diameter influences the effectiveness of penetration into compacted soils and find that pressure from compaction lead to increasing size of root tips of taprooted plants.

Together with carrots, beetroots are considered a beneficial break crop in rotations primarily for grain production, as neither one of the crops are hosts for any of the common cereal pests or are high in demand of nitrogen (N) (Olsson 2004; Robson et al. 2002). Carrots should be rotated in periods of 7 years to avoid certain diseases, and beets in periods of 5 years, ultimately (Ögren & Jonsson, 2015). Beets are quick in the uptake of N and begin already at four or five leaves, but the supply of N must be continuous during canopy closure for the crop to establish sufficiently (Sweeney et al. 2008). Both crops are however rather sensitive towards competition from weeds (Ögren & Jonsson, 2015). Perennial wheatgrass, however, is known to suppress weeds efficiently due to a dense and laterally expanding root system (Oliviera et al. 2018) (yet it can reemerge itself as a weed through rhizomes). The machines used for harvesting carrots and beets are heavy and can cause soil compaction, but the positive effects of deep-rooted perennials might to some extent mitigate this risk when these crops are incorporated in the same rotations. After only two years, intermediate wheatgrass intended for perennial cropping have developed root systems that are deeper and denser compared to conventional, annual cereal crops (Duchene et al. 2020). Perennials often have more moderate resource requirements and allocate larger proportions of biomass belowground, giving better chances of soil aggregate formation and build-up of soil stability. Since perennials also offer ground cover during a longer period each year compared to annual grains and start to extract nutrients and water from the soil earlier during the growing season (Duchene et al. 2019), they have unique advantages in competition with the annual weeds that usually dominate annual grain cropping systems.

Soil & microorganisms

What determines the distribution of roots in soil is the physical properties of it: bulk density, aeration, and the stability of aggregates (Perkons et al. 2014). Tillage tends to increase microbial activity through added oxygen but also show higher losses of nitrogen as NH_3 and CO_2 , while agricultural systems with no or reduced tillage tend to show higher stability and functionality (Chahal et al. 2021). Increased microbial activity in perennial agricultural systems may be related to both increased amounts

of carbon inputs, both above and below ground, and reduced tillage. Results of the study by Chahal et al. (2021) show ties between high soil organic carbon and increased microbial activity with increasing crop yields. Likewise, Zhong et al. (2010) associate increased soil microbial communities and functional diversification with increased crop yields in their experiment of 21 years with different N fertilizers on maize in the Jiangxi Province of China. The purpose of their study was to examine how microbial communities were affected by organic manure and mineral fertilizer. Here, it was found that adding organic material together with a balanced addition of N, P and K in mineral form increased the yields for maize. However, in the same study PLFA (Phospholipid Fatty Acid) analysis indicated that growth of soil bacteria diminished under the treatment of only applied mineral N. Looking at the plots treated solely with nitrogen fertilizer in the study by Chahal et al. (2021), seeing a loss of organic carbon in the soil, they hypothesize that the depletion could be a result of an increased mineralization.

In a study by Sprunger et al. (2018) it was found that perennial grass, in this case intermediate wheatgrass, was to a larger degree affected by variations in nitrogen fertilization. Where the application rates were lower (in their experiment the lowest volume was 21 kgN/ha, while the intermediate level was 90 kgN/ha and the high N level was 135 kgN/ha), the C:N quotas were higher. The fact that perennial grasses contain more lignin, and that the breaking-down process requires more nitrogen, is increasing the competition in the soil, further restricting crop access to this nutrient (Ryan et al. 2018). In another study by Sprunger et al. (2019), spanning over three years, the quality and biomass of roots, communities of bacteria and nematodes as well as accessible carbon was compared under perennial intermediate wheatgrass and winter wheat. Part of the results showed that management type (different N regimes, particularly organic nitrogen inputs) had a greater ability to positively influence bacterial and nematode communities compared with annual or perennial crop type, although both had impact. Eventually, during the third and last year of the study, plant type had a detectable effect on bacterial community structure; likely this late connection is caused by a temporal difference in how N management and plant type influence nutrient conditions in the soil. In the same study, Kernza indicated higher storage of soil carbon (C), compared to annual wheat, and contributed to diversity among bacterial decomposers by providing roots of different stages of decay. Two types of bacterial feeders were also represented in the indicator taxa for perennial systems, indicating that although the nutrient cycling of the two different cropping systems did not seem to diverge in this study, nutrient cycling among perennials might be stronger. The authors point out however that in studies spanning over more than three years, crop type could be shown to have a stronger influence. The study also showed that applying organic nitrogen induces larger roots and has effects on how carbon is stored in the soil.

Sweeney et al. (2008) specify that the break-down of pre-crop roots might utilize the available nitrogen and cause a depletion for the following crops. Glover et al. (2010) link perennial grasses to higher utilization of N below the root zone by looking at levels of NO₃-N at the end of the growing season. They also conclude higher levels of soil organic carbon (SOC) in perennial fields compared to annual fields without tillage. Also, higher levels of N in harvested biomass were observed

in the same study. Perennial grasses can utilize nitrogen in deeper soil levels compared to annual cereals with shallow root systems (Zimbric et al. 2020; Sprunger et al. 2018; Glover et al. 2010). When the perennial grass rotation is terminated, nitrogen is released and becomes available for the following crop, during a relatively short period (Lemaire et al. 2015). In a study by Crews et al. (2022), the authors state that two and three years after termination of IWG, mineralization of N had increased due to a growth in the soil organic nitrogen pool. This could indicate that harvests from the subsequent crop might increase due to increased N access through breakdown a year or two years after intermediate wheatgrass termination. The authors also highlight that due to minimal soil disturbance during the perennial regime, and via continual harvest of biomass, these trial fields became N limited. It is however worth considering that, according to DuPont et al. (2014), the roots of perennial grasses can remain for over five years in the soil after termination (looking at long-term conversion studies), and that roots remaining in the soil can block biopores until further degraded. Perkons et al. (2014) studied the root-length densities of annual crops when grown subsequent to crops of different root type. Using the annual field crops spring wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and winter oilseed rape (*Brassica napus* L.), following either oats (*Avena sativa* L.), tall fescue (*Festuca arundinacea* Schreb), or chicory (*Cicorium intybus* L.), the authors look into the development of biopores and study how different types of crops affect them. It is found that roots tend to develop inside biopores formed by pre-crops, benefitted by increased access to water and reduced mechanical resistance, but that dead roots can also remain blocking biopores until decomposition. Looking at the capacity of fixating nitrogen as well as the capacity to transfer it, Louarn et al. (2014) compared alfalfa and white clover in a study spanning over 3 years. In this study, it is found that these nitrogen fixing crops, grown together, develop differing strategies for survival in the long term; white clover has a higher turnover of fine roots while alfalfa grows a large taproot and invests more in other typical perennial traits. Fine roots in white clover have a quicker turnover rate, and it also shows higher deposits of shoots and stalks. The authors conclude that plant residue type and quality have an influence on the use of the nutrients for the following crops, and that these factors have the potential to alter nitrogen cycling. Sprunger et al. (2019) conducted a study focusing on the influence of different nitrogen management regimes on communities of bacteria, fungi, and nematodes as well as root formation, comparing wheat with the intermediate wheatgrass Kernza. One of the discoveries was that the response of bacterial communities had a stronger connection to different N application rates rather than plant type. However, the two are interconnected due to the influence of root quality and quantity on soil nutrient pools.

In an experiment by Glab et al. (2007) the influence of compacted soils on harvest of perennial wheat was investigated by studying fields under varying intervals of machine traffic. It was found that repeated forage harvests and thereby increased passes by heavy machinery on the field increased bulk density in soil layers of 5-10 cm of depth, while the bulk density of depths between 0-5 cm was not as high. At a certain point, compactness increased the yield of tall fescue that was used in this study, only to decrease harvest again after another turning point.

In a field trial conducted over 5 years, Crews et al. (2022) investigated the nitrogen economy of perennial intermediate wheatgrass (IWG) and the perennial and nitrogen fixing legume alfalfa (*Medicago sativa*). One of the objectives was to find out how the mass balance of the annual and cumulative N allocation of three designs (one with intercropped alfalfa, and two with only IWG, planted in rows of 38 or 76 cm) compared under different fertilization treatments. By deducting the harvested amount of N from the input of N through urea fertilizer, N fixation by alfalfa measured by shoot biomass, or added alfalfa mulch, the N balance was calculated each year. The authors conclude that in the plots with intercropped alfalfa and IWG, similar observations of N₂O emissions as in unfertilized monoculture plots were made, suggesting that after crop establishment the supply of N matches the demand. It was also observed that by intercropping alfalfa, total root biomass in the top 10 cm increased significantly compared to plots without alfalfa. However, there is an observable retention period where N supply is accumulated as organic nitrogen in the intercrop. The authors also state that N limitation occurred in plots with monocultured IWG through both reduced mineralization of crop residues due to decreased soil disturbance, and annual harvests.

Weed dynamics

An advantage of creating crop rotations including perennial cereal Kernza and root crops such as carrots and beets are the possible avoidance of long-lived weed seeds that tend to build up when beets are recurrently grown (Robson et al. 2002). Kernza has a tendency of shifting the weed community composition towards perennial species, which can counteract the build-up of a long-lasting weed seed bank. In addition, Kernza is anticipated to better utilize nitrogen through below-ground competition, leading to the suppression of weeds over time (Zimbric et al. 2020; Ryan et al. 2018). In agrarian cropping systems dominated by perennial crops, in particular cereal crops, the selection pressure is expected to put annual weeds that have an erect growing pattern and primarily apical meristems, heavy seeds, and late flowering to a disadvantage (Armengot et al. 2016). The selection against these traits is also greatly influenced by other differences in management between annual and perennial crops, such as less frequent soil disruptions (Zimbric et al. 2020) — something that also risks increasing weed coverage (Kakabouki et al 2015). Weeds have evolved under more varying conditions and therefore their ability to exploit nutrients and adapt to altering surroundings is often stronger compared with cultivated crops (Kaur et al. 2018; Li and Watkinson, 2000).

When one important resource becomes limited, competition between crops and weeds escalates, normally leading to an increase in weed biomass due to higher adaptation and N exploitation capacity in weed species compared to crops (Kaur et al. 2018; Lehoczy et al. 2013). According to Armengot et al. (2016), weed communities in conventional cropping systems that include nutrient application and ploughing have higher nutrient affinity, probably related to higher mineralization rates. This can imply greater competitive intensity between the crops and weeds in such systems. If the amount of N is not strictly limiting growth, competition between weeds and crops may shift slightly towards competition for light, animating a greater above-ground growth in weeds under conditions with greater access to N (Cheimona et al. 2018; Kaur et al. 2018; Lehoczy et al. 2013). In a

study performed by Lehoczky et al (2013) harvest biomass and nutrient content of maize (*Zea mays* L.) was compared on two plots, one which was left untreated and one where herbicides were applied. The study showed that competition from weeds greatly reduced the growth of maize, and that maize contained a lower percentage of all measured nutrients. Competition for N was primary, and negative effects caused by competition from weeds was observable even early in early growth stages. In a study by Okafor and De Datta (1979) it was discovered that competition for water increased between rice and purple nutsedge when applied nitrogen increased (from zero applied nitrogen to 60 kg N/ha). Zimbric et al. (2020) also states that weed species that can efficiently exploit nutrients are usually also very efficient in utilizing other resources, such as light and water. In a study by Li and Watkinson (2000) the competitive abilities of carrots (*Daucus carota*) and lambsquarters (*Chenopodium album*) were investigated over a nutrient gradient from 1/256 parts up to 64 times higher than the standard N concentration, as well as with varying densities of the carrot and lambsquarters populations. Both at low and high levels of nutrients lambsquarters were more competitive compared to carrots, but when nutrient levels were intermediate carrot would produce higher yields in comparison, due to a slight overtake in competitive ability at these nutrient levels. When nutrient levels were lower, the competition within populations of the same species was more conclusive than competition between the different species.

Early applications of nitrogen might help reduce losses through denitrification and leaching due to lower precipitation and soil temperatures, but it risks initiating weed emergence (Sweeney et al. 2008). Looking into the dynamics of applied nitrogen fertilizer and the release of soil inorganic nitrogen and its influence on weed seed emergence, Sweeney et al. (2008) used soybean (*Glycine max*) as a pre-crop for maize (*Zea mays*) and sugar beets (*Beta vulgaris*). Here, it is considered that immobilization of applied nitrogen might have occurred when soil temperatures rose to around 13 °C in late April and May. This immobilization of applied nitrogen may be caused by the microbial activity of breaking down pre-crop residues. Roots of perennial grasses such as Kernza contain higher C:N quotas compared to wheat roots, meaning that root residues have a slower decomposition rate (Sprunger et al. 2019). Dimitrova Mårtensson et al. (2021) study the effects of different intermediate wheatgrass termination strategies and hypothesise that yields, as well as IWG recurrence and weed presence, will be highest after spring termination. Their findings differ from the previously mentioned studies in that they found higher presence of annual weeds in the study plots previously cropped with IWG. They consider this to follow a high competence of IWG to out-compete perennial weeds and conclude that shallow tillage followed by harrowing should be enough to reduce recurring tillers of IWG, as well as reduce weeds due to the creation of stale seed beds. However, the subsequent crop beetroot seems to benefit from the deeper ploughing regimes in this pilot study, although often being found to perform better considering yield when grown under organic management with lower soil impact. Yet, competition for light or nutrients might have been a cause of these dynamics as well.

Field study

Crop yields

The total yield of carrots and beetroots were significantly higher in the crop rotation with annual crops compared to when grown after the perennial cereal Kernza (Table 1). Similarly, the yield of approved specimens was higher when incorporated in the annual cropping system compared to the perennial cropping system. The dry weight of the tops was also higher when crops were grown in the annual system. Visual notes of the approved harvest specimens were made; these notes were not quantified but fewer notes were made regarding the crops from the perennial pre-crop rotation (1 note), compared to crops from the annual pre-crop rotation (4 notes).

Table 1.

Mean values of harvest variables Total harvest weight, Weight of approved specimens and Dry weight of tops for the annual pre-crop treatment (A) and the perennial pre-crop treatment (P) and beetroots and carrots respectively. Different letters (a, b) show differences resulting from ANOVA with Tukey Post-hoc test at the significance level of $p < 0.05$. The number of plots with beetroots in the perennial pre-crop treatment were 5, and 4 for carrots; carrots had 5 plots in the annual pre-crop treatment, whereas beetroots had 4 plots.

Harvest variable (g)	Treatment/crop	Mean value (g)	n
Total harvest weight	A/beet	452 ^a	4
	A/carrot	450 ^a	5
	P/beet	146 ^b	5
	P/carrot	145 ^b	4
	Weight of approved specimens	A/beet	310 ^a
	A/carrot	385 ^a	5
	P/beet	53 ^b	5
	P/carrot	113 ^b	4
Dry weight of tops	A/beet	54 ^a	4
	A/carrot	26 ^a	5
	P/beet	12 ^b	5
	P/carrot	6 ^b	4

Beetroots

Most of the beetroots of approved quality from the perennial pre-crop treatment were of the small diameter class (2-4 centimetres in diameter) (Figure 1). The total number of approved specimens were 7; 4 of the small size class and 3 of the medium size class (4-6 cm in diameter). Beetroots of approved quality from the annual pre-crop treatment were 25 in total; 9 were in the small size class, 14 in the medium size class and 2 in the large size class (6-8 cm in diameter). The mean weight for beetroots of approved quality from within the perennial pre-crop treatment was 53.0 grams (one of the sample plots contained zero approved specimens), while approved beetroots from within the annual pre-crop treatment had a mean weight of 310 grams. Mean weight of approved beetroots was significantly higher in the annual pre-crop treatment compared to the perennial pre-crop treatment ($p < 0.05$).

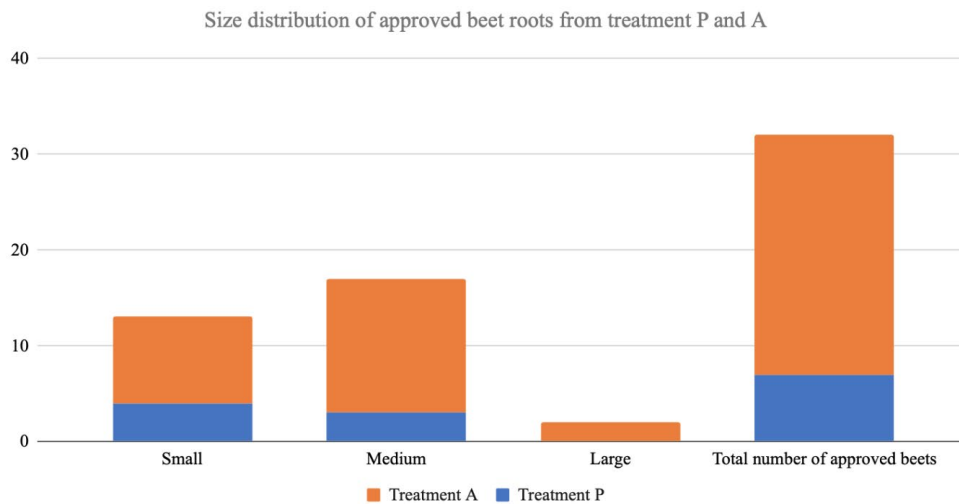


Figure 1.

Size distribution of approved beetroots from the perennial pre-crop treatment (blue bars) and the annual pre-crop treatment (orange bars) respectively.

Carrots

The majority of approved carrots from the perennial pre-crop treatment (8 out of a total of 9 approved specimens) were in the small size class (10-15 cm in length and 1.5-4 cm in diameter) while most of the carrots of approved quality from within the annual pre-crop treatment (7 out of a total of 14 approved specimens) were distributed to the medium size class (15-20 cm in length and 4-6 cm in diameter). The perennial pre-crop treatment had 1 specimen in this size class. Only the annual pre-crop treatment contained carrots of approved quality that were classified per the large size class (with length between 20-30 cm and diameter between 6-8 cm), although only one carrot out of fourteen were graded to this size class.

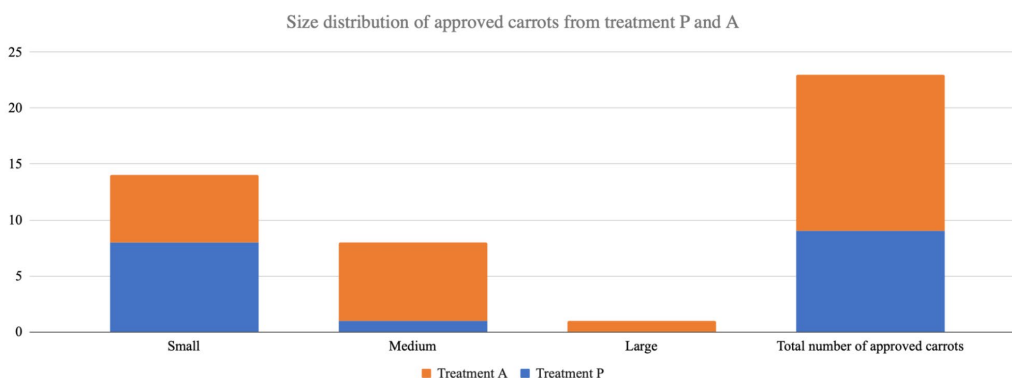


Figure 2.

Size distribution of approved carrots from the perennial pre-crop treatment (blue) and the annual pre-crop treatment (orange).

Weed occurrence & abundance

The annual pre-crop treatment had significantly higher mean biomass of weeds (45,7 g) compared to the perennial pre-crop treatment (15,7 g), as per measurements made during the growing season (July). The perennial pre-crop treatment was dominated by weeds with a perennial life cycle both in plots with carrot and beet, while the plots with annual pre-crop treatment was dominated by annual weeds, both in plots with carrot and beet. The mean percentage cover of annual and perennial weeds was however higher in the perennial treatment (23,3% cover of perennial weed species and 10,2% cover by annual weed species in the perennial pre-crop treatment, versus 13,1% cover by annual weed species and 1,7% cover by perennial weed species in the annual treatment; see table 2).

Table 2.

Mean cover of perennial and annual weeds for the annual pre-crop and perennial pre-crops treatment and beet and carrot plots, respectively. The perennial pre-crop treatment plots have a higher presence of perennial weeds, while the annual pre-crop treatment is covered to a greater extent by annual weed species. Standard deviations show large variations within the categories. The number of plots per pre-crop/crop is 3, but the number of observations is based on the number of perennial or annual weed species (3 and 7, respectively) with a percentage cover of 10% or higher in any plot.

Treatment/ crop	Mean % cover of annual weed species	Standard deviation	Mean % cover of perennial weed species	Standard deviation	n
A/beet	13,1	28,9	1,7	3,5	9
A/carrot	14,3	30,9	0,6	1,7	9
P/beet	8,8	10,9	23,3	30,8	9
P/carrot	10,2	14,0	23,3	26,0	9

The weed with the dominating mean percentage cover for the annual pre-crop treatment, in both carrot and beet plots (87 and 80 respectively), was *Chenopodium album*, an annual weed with florescence between July and September. For the perennial pre-crop treatment plots, the weed *Veronika chamaedrys* had the dominating mean percentage cover for both carrot and beet plots (43,3 and 56,6 respectively). *Veronika chamaedrys* is a perennial weed with florescence between May and June.

Perennial re-emergence

Both the perennial and annual pre-crop treatments were controlled for emergence of Kernza tillers during the growing season. Only three tillers were observed, all emerging within the perennial pre-crop treatment. Two of the fields containing tillers were cropped with carrots, and one with beets. The total number of observations were 12, 6 for each treatment.

Soil characteristics

No correlations between any of the soil properties and harvest variables were detected for either of the two treatments. Loss of ignition (%; LOI) was higher in the soil of the perennial pre-crop treatment (P) compared to in the soil of the system with annual pre-crops (A) (see Table 3). Soil respiration (parts per million of CO²-carbon per day) was significantly higher in the perennial pre-crop treatment (P) compared to the annual pre-crop treatment (A) ($p < 0,05$), both in July and September. Water content (%; WC) was significantly higher in the perennial pre-crop treatment. This is true for tests performed in July and September alike ($p < 0,05$) (Table 3). Bulk density of the perennial pre-crop treatment and the annual pre-crop treatment was measured before the sowing of the subsequent crops (May), during the growing season (July) and before harvest (September). No significant difference in bulk density was detected between the treatments on neither occasion, for any of the other soil parameters.

Table 3.

Mean values for soil properties (LOI (%): Loss on ignition; WC (%): water content; respiration (parts per million CO²-carbon and day); pH; bulk density in grams per cubic centimetre) of the perennial pre-crop treatment (P) and the annual pre-crop treatment (A), beets and carrots collectively. Where no crop is listed, the properties were measured before the crops were planted (May). Where no value is listed, no samples were collected. The difference in number of observations is due to a different number of samples taken on each occasion. Different letters (a, b) indicate effects on the root vegetable performance of pre-crop using ANOVA with Tukey Post-hoc test at the significance level $p < 0.05$.

Soil properties	Treatment/crop	Mean value	Month	n
LOI (%)	A/	3,3 % ^a	May	3
	P/	4,3 % ^a	May	3
	A/both crops	4,4 % ^a	July	6
	P/both crops	5,6 % ^b	July	6
	A/both crops	4,6 % ^a	Sept	9
	P/both crops	5,8 % ^b	Sept	9
WC (%)	A/	15,0 % ^a	May	3
	P/	18,1 % ^b	May	3
	A/both crops	14,8 % ^a	July	6
	P/both crops	16,6 % ^b	July	6
	A/both crops	14,9 % ^a	Sept	9
	P/both crops	16,5 % ^b	Sept	9
Respiration (ppm/day)	A/	21,4 ppm/day ^a	May	3
	P/	53,8 ppm/day ^b	May	3
	A/both crops	58,1 ppm/day ^a	July	6
	P/both crops	96,9 ppm/day ^b	July	6
	A/both crops	59,5 ppm/day ^a	Sept	9
	P/both crops	98,7 ppm/day ^b	Sept	9
pH	A/	5,6 ^a	May	3
	P/	5,6 ^a	May	3
	A/both crops	-	July	6
	P/both crops	-	July	6
	A/both crops	5,2 ^a	Sept	9

	P/both crops	5,2 ^a	Sept	9
Bulk density (g/cm³)	A/	1,5 (g/cm ³) ^a	May	3
	P/	1,3 (g/cm ³) ^a	May	3
	A/	-	July	6
	P/	-	July	6
	A/both crops	1,3 g/cm ³ ^a	Sept	9
	P/both crops	1,2 g/cm ³ ^a	Sept	9

Nitrogen, carbon, and C:N quota

Levels of carbon (C) and nitrogen (N) found in samples taken before and after the establishment of the experiment are significantly higher for the perennial pre-crop treatment compared to the annual pre-crop treatment (Figure 6). The quota of C and N is also significantly higher in the perennial pre-crop treatment.

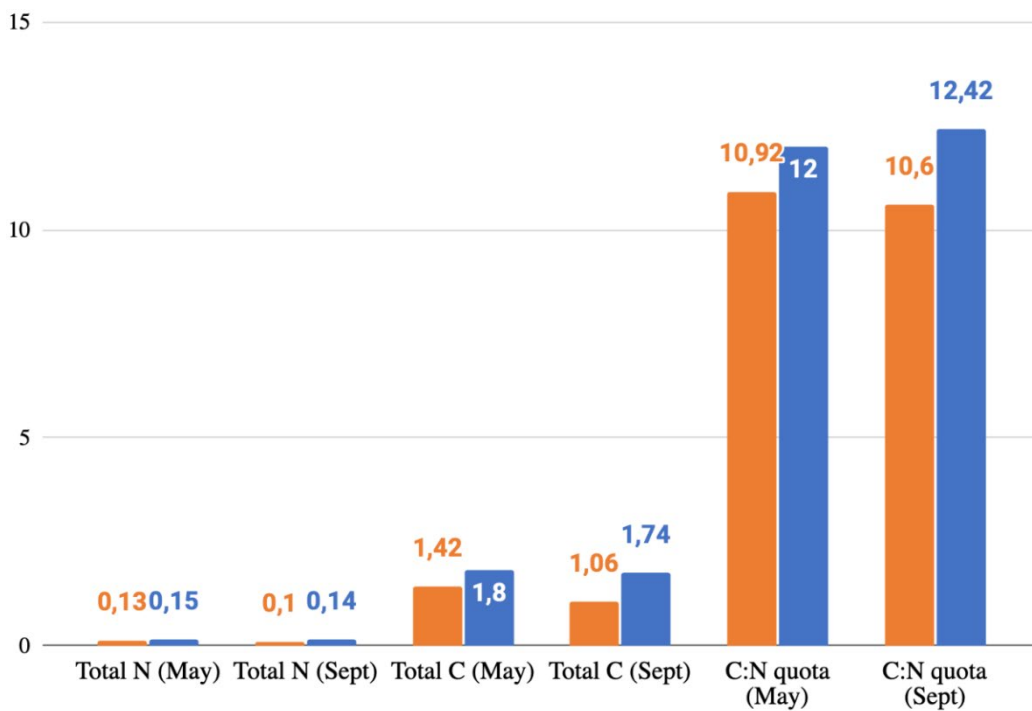


Figure 3.

Mean values of total C, total N and C:N quotas for the pre-experimental perennial system (blue bars) and the pre-experimental annual system (orange bars), in May and September. Degrees of freedom for all statistical testing is 1.

Discussion

Harvest of carrots & beetroots

Perkons et al. (2014) discuss the influence different types of biopores have on subsequent crops in crop rotations. The organic matter content of the perennial pre-crop treatment in our study was significantly higher compared with the annual treatment. Considering the sensitivity towards resistance that is found both in carrots and beetroots, it is possible that the remnants of Kernza roots caused mechanical growth resistance. By visual assessment of the whole field harvest, it was concluded that the crops in the fields following the perennial pre-crop treatment were sparser and of smaller size compared with crops from the annual pre-crop treatment. This was confirmed statistically for total harvest weight and weight of approved specimens and by the aboveground biomass (dry weight of tops) (see Table 1 for mean values). Weight of crops following the annual pre-crop treatment were significantly higher compared to crops grown within the perennial pre-crop treatment ($p < 0,05$). No assessments of the entire treatments were made, but the harvest samples from the annual pre-crop treatment received a higher number of notes regarding visual damages (4, compared to 1 note for specimens from within the perennial pre-crop treatment), however, damages were not quantified or compared between treatments. This may merely be an effect of a larger sample due to higher harvest weights.

Weed dynamics

Both Armengot et al. (2016) and Zimbric et al. (2020) have conducted studies that look into the effects of different management regimes, specifically reduced tillage, on weed dynamics, and the weed management risks that follow cropping of intermediate wheatgrass (IWG), respectively. As mentioned, one of the patterns discovered is an increase of perennial weeds on fields with perennial crops (in this case, IWG). The distribution of annual and perennial weeds between the two different areas in our experiment seem to follow the pattern described by Armengot et al. (2016) and Zimbric et al. (2020), i.e., where the perennial pre-crop Kernza is cropped for six consecutive years we observe more perennial weeds (see Table 2). This is possibly a result of differences in management regimes; a combination of less frequent soil disruptions and lower levels of applied nutrients, putting pressure on inter-species competition towards benefitting deeper root systems and utilization of soil water and nutrients earlier in the growing season. The results may also be influenced by a higher presence of weeds on plots with the annual pre-crop, in general. We should consider the mentioned results of Zimbric et al (2020) where weed density was observed to be higher after autumn forage, at a time when levels of nitrogen were lower, in comparison to spring forage during times when applied nitrogen levels were higher. Relating this to our study, we can contemplate that the weed density might have initially been comparable to that of the annual pre-crop treatment since lower amounts of nitrogen was applied to the perennial system and second harvests took place during autumn. Yet, the fact that the perennial system was terminated during spring might have decreased weed density and diluted such an effect, leading to a lower biomass of weeds at the time of sampling.

The selection against weeds that have an upright growth pattern may have been reinforced by the harvest of biomass (Cheimona et al. 2018; Armengot et al. 2016) that took place during the entire duration of the rotation (2015-2020). However, if we consider both the higher levels of N under the perennial pre-crop treatment and the larger amount of weed biomass under the annual pre-crop treatment, a shift in competition tactics is not obvious in our study. If such a shift took place, it might have been hidden by the management regime in the perennial system; forage harvest of Kernza twice per growing season might have put negative pressure on tall weeds. However, the finding of a higher mean percentage cover of weeds following the perennial pre-crop treatment, yet a lower total weed biomass of 15,1 grams, may suggest that weeds colonizing the perennial pre-crop treatment plots were larger in size although lower in biomass. Still, these results could also indicate that there has been a selection for smaller weed species that instead cover larger areas of the ground.

It is likely that the pre-experimental systems have shaped the nitrogen and weed dynamics and that these lingered even in our study. Our results also show high standard deviations in the measurement of the presence of perennial versus annual weed species, which also hinders our ability to draw conclusions. Also, the fact that the P plots had a higher presence of perennial weeds, this enhanced the negative effects of competition with the subsequent crops carrots and beetroots due to weeds already being established and deeply rooted (Lehoczky et al 2013).

The low harvest weight in both treatments might be a demonstration of the phenomenon of escalating competition due to limited access to N (Kaur et al. 2018; Lehoczky et al. 2013); competition from weeds have seemingly reduced growth in carrots and beets, in both cases likely due to low nitrogen levels where weeds are more exploitative, and in the case of the annual pre-crop treatment possibly also due to light competition. Considering the results in our case it is plausible to believe that competition from weeds together with nitrogen dynamics had the greatest influence on harvest loads, i.e., both life strategy of pre-crop and associated management influencing the harvest. In these plots, higher levels of nitrogen in the annual pre-crop treatment might have explained the greater biomass of weeds – however, these were not our results.

The association between increased competition from same species crops or weeds with varying levels of available nitrogen described by Li and Watkinson (2000) might offer an explanation to the larger amount of weed biomass produced under the annual pre-crop treatment; considering that the amount of nitrogen, even though it was lower compared to the perennial pre-crop treatment, might have been more accessible to the emerging subsequent crops due to not being confined in root residues. Furthermore, in the aforementioned greenhouse experiment by Sweeney et al. (2008), it was found that the dormancy of lambsquarters seeds seems to be prolonged when mother plants suffer from a lack of nitrogen. This might have been a consequence of inaccessibility of nitrogen in the perennial pre-crop treatment, enhanced by lower nitrogen application and higher utilized levels of nitrogen of preceding years. Lower amounts of weed biomass in the perennial pre-crop treatment might be the result of such an effect. Lower weed densities in perennial

cropping systems might be due to a greater ability in perennial grasses to utilize N applications and thereby to suppress weeds (Zimbric et al 2020), and this effect might be perpetuated in subsequent crops.

Terminating Kernza only 19 days before sowing of the subsequent crops mitigates an issue otherwise present when incorporating root crops in cereal crop rotations, namely baring the soil for approximately eight months before the sowing of root crops around March or April (Robson et al. 2002). Consequently, the termination of Kernza in spring might help mitigate erosion and nutrient losses. Sweeney et al. (2008) state that later application dates for nitrogen and slow-release fertilizers can alleviate the presence of early emerging weeds within integrated cropping systems. Yet, considering the nitrogen dynamics, the retention of C in roots and low access to N due to high utilization by Kernza over several years, it might propose new problems; competition over nitrogen between the emerging subsequent crops and microorganisms (Galland et al. 2019). Also, when viewing termination of Kernza as a possible fertilizing nitrogen addition, the initial access to ammonium and nitrate is lost on crops when sowing of beets and carrots takes place 19 days after the termination of Kernza, and is rather converted to gaseous N, N₂O or immobilized through microorganisms.

In a study conducted by Dimitrova Mårtensson et al. (2021), termination timing and its effect on re-emergence of Kernza tillers and weed biomass was examined. Harvest ploughing, referred to as the conventional termination strategy, led to the lowest count of Kernza re-emergence, while weed biomass was similar between the different treatments (spring harrowing, autumn harrowing and autumn ploughing). This study indicated that termination strategy is not detrimental to avoiding re-occurring Kernza or lowering weed biomass, yet it might be important to consider in relation to harvest levels. In the same study, the harvest of subsequently sown beetroots was highest after autumn termination by ploughing. As previously mentioned, this may also be related to immobilization of nitrogen caused by an inappropriate amount of time between termination and sowing of subsequent crops.

Soil & microorganisms

As the bulk density did not differ significantly between the two treatments at any point, it is not given that higher mechanical resistance in the soil should be the reason for lower yields of the root vegetables in the perennial pre-crop treatment. The perennial pre-crop treatment had significantly higher organic matter content according to the LOI-tests performed in September and July (the LOI-tests made before the establishment of the study were higher for the perennial pre-crop treatment, but not significantly); which seems in accordance with the research of DuPont et al. (2014) as well as Perkons et al. (2014). We should consider the effects of these remaining roots on nutrient availability through retention as well as mechanical resistance to the establishing subsequent annual crops. Yet, that the residual roots of Kernza is causing the lower establishment and smaller size of carrots and beetroots is not evident considering there was no statistical difference between the large (> 2 mm) and small (< 2 mm) soil fractions between the perennial and the annual pre-crop treatments. If there had been, it might be explained by a higher percentage of root biomass in the perennial pre-crop treatment. However, it

should be noted that the ploughing, performed on both fields before the establishment of the treatments, only reached 10 cm of depth on the perennial field due to resistance from roots (Rasmussen, E., 2021, *pers. comm.*). This is also the depth of the bulk density samples, which might affect the results. In deeper levels, we do not know if bulk density would differ, and considering the research of Glab et al. (2007), it might be considered so. If bulk density had been measured on deeper levels it might have shown larger differences between the two pre-crop systems.

Another possible explanation for the lower yield of crops grown within the perennial pre-crop treatment might be related to the nitrogen dynamics in the field influenced by Kernza. Utilization of nitrogen from deeper levels in the soil, due to coarser and bigger perennial root systems, can release nitrogen back to the plant available pool after termination of the perennial rotation (Lemaire et al. 2015). This plant available nitrogen might however be lost due to leakage since carrots are rather slow in their establishment (1 to 3 weeks from sowing to emergence and 3 to 4 weeks before true leaves are developed) (Robson et al. 2002) and considering 19 days passed between termination of Kernza and sowing of subsequent crops (see [Appendix 2](#)). Even if the applied nitrogen fertilizer had been of equal amounts during the years before the establishment of the field study, the perennial pre-crop treatment might have caused a disadvantage due to N being depleted to a higher degree through increased microbial retention during decomposition after Kernza termination. Beets are quick in the uptake of N and begin already at four or five leaves, but the supply of N must be continuous during canopy closure for the crop to establish sufficiently (Sweeney et al. 2008).

Taking the observations of Glover et al. (2010) and Sweeney et al. (2008) into consideration, we must contemplate that the perennial pre-crop system might have been lower in nitrogen due to both higher utilization and higher retention in roots, and because of higher microbial competition. Considering higher employment of N from deep soil layers and biomass together with the management history of the fields where the perennial pre-crop treatment was established, with reduced application of nitrogen fertilizer (see [Appendix 2](#)), there is reason to believe that the perennial pre-crop treatment led to lower nitrogen levels, possibly affecting growth of beets and carrots. In contrast, the annual pre-crop treatment was in tread during the year before the study and was previous to that fertilized with higher amounts of mineral N ([Appendix 2](#)). This might have placed the annual pre-crop treatment fields in an advantageous position. However, the harvest from both the perennial pre-crop treatment and the annual pre-crop treatment were rather low, and no typical signs of nitrogen deficiency was observable in the harvest sample foliage. It is likely that the low levels of nitrogen are connected to the observed yield loss, but through intricate relationships between competition from weeds and microorganisms. Also, considering the experiments by Crews et al. (2022) where nitrogen mobilization increased as the pool of organic nitrogen in the soil grew larger, we might have seen an increase in yield of subsequent crops in years after termination of Kernza. Another aspect discovered by Crews et al. (2022) was that because of discontinued soil disturbance and therefore lower rates of mineralization, as well as removal of N through annual harvests, one of the treatments with intermediate wheatgrass shifted towards increasing N limitation. In

this case, no additional N was added to the treatment, as in our case at Lönnstorp - yet it is still possible we see a similar effect. Although, in spite of the perennial treatment receiving lower amounts of mineral nitrogen fertilizer throughout the years, our samples show that these plots contain significantly higher amounts of nitrogen compared to the annual treatment. In accordance with Chahal et al. (2021) the perennial system, not having been tilled for 6 consecutive years, contains higher amounts of nitrogen as well as carbon. In their study, they use two long-term study sites in Ontario where soybean and corn were used as base crops in different types of crop rotations with varying management regimes (concerning tillage, cover crops and nutrient additions). It was found that diversifying rotations increased both indicators for soil health (soil organic carbon, total nitrogen and increased microbial activity, for example) as well as crop yields. This is not something we can demonstrate in our study, where yields of subsequent crops were lower following the perennial cereal crop. The authors state that “the exact mechanism through which applied nitrogen in diverse crop rotations impact soil microbial activity is unclear but might be related to differences in the type and amount of root exudates, rhizodepositions, and amount of crop residue inputs”, concluding that more research is needed.

Nitrogen is usually the most limiting nutrient concerning plant growth, and is heavily competed over with microorganisms (Galland et al. 2019). In results found in the study by Zhong et al. (2010), it was mainly an addition of organic matter and mineral nutrients NPK that increased microbial activity, likely due to increased production of organic matter and following this, increased amounts of root exudates in the soil. This demonstrates the role soil aggregate structure and stability plays for microbial communities. Chahal et al. (2021) conclude there is a soil carbon depletion following treatments receiving N applications and without tillage, something we do not see in our study; however, we might see a similar microbial immobilization.

Dimitrova Mårtensson et al. (2021) also conducted their studies at Lönnstorp and concluded that the seed bank on the location is rather large. They study how the timing of termination of Kernza influences the weed community, comparing different types of late and early season tillage. The cropping of Kernza seems to have shifted the weed community from domination of annual weeds to perennial weeds, which can influence subsequent crops via life strategy advantages (earlier utilization of plant-available nutrients, for example). However, it is difficult to separate such an effect from the influence of nitrogen retention in root residues. It is possible that termination of Kernza in autumn would change these dynamics immensely, but it would then also be necessary to study the loss of nitrogen through leakage via runoff, for example. It is also possible that retention of N would continue to cause a shortage for subsequent crops, due to downbreaking activities being slower in colder temperatures. Possibly, however, there may have been a decrease of LOI (%) in the perennial pre-crop plots, and larger harvest weights of subsequent crops.

Conclusion

Beetroot and carrot grown following the perennial wheatgrass Kernza were of fine quality but of fewer numbers and small in size, despite soil parameters soil organic matter, water content, microbiotic respiration, nitrogen levels and C:N ratio being higher compared to plots where annuals were grown previously. This indicates that termination of Kernza 19 days before sowing potentially caused a deficiency in plant available nitrogen, through detention in root residues and microbial immobilization. Terminating Kernza earlier during spring, alternatively during the previous fall, would give comparable data on how nutrient cycling by microorganisms can best be utilized in this crop rotation. Also, several studies indicate that measuring bulk density in the topsoil (upper 10 cm) is not enough to understand the growing conditions of roots, as compactness can differ a lot looking at deeper soil levels. Aggregate stability was not measured in this study, another factor that could have given indications as to how the condition of the soil differs between the two types of pre-crops used.

The root type of subsequent crops and different development strategies and adaptation to pre-crop root biopores would also indicate which types of crops to incorporate in crop rotations that include perennial wheatgrass. Evaluating the suitability of Kernza as a pre-crop to crops with smaller root systems would potentially give information about the soil and nutrient dynamics locked into pre-crop type, soil factors and factors connected to subsequent crops. Also, incorporation of nitrogen fixating crops in comparable plots would enhance the overview that we have available today. There is plenty of research incorporating nitrogen fixing crops in rotations also including Kernza; however, re-thinking our agricultural systems to better align with the needs of today, considering both social and environmental sustainability, most likely also includes incorporating more crops suitable for direct consumption as well as perennial cereals into agricultural production systems. Doing this requires more research on how different types of root and soil dynamics are created, in means of soil aggregate structure, timing of termination of perennials, efficient nutrient cycling in correlation with microorganisms. In future research, suggestively soil aggregate stability and timing of termination in relation to establishment of subsequent crops should be investigated, also with N addition to subsequent crops.

Popular scientific abstract

A literature and field study looking at pre-crop qualities of intermediate wheatgrass Kernza™, through measurements of soil parameters and qualitative harvest measurements of subsequent carrot and beetroot crops.

Looking at how political and climatical changes affect our food chains, resilience needs increasing - both relating to lowering dependence on fossil fuels and incorporation of perennial plants that have a lower negative impact on soil health and that can be hardier under a changing climate. This study looks at how intermediate wheatgrass Kernza™ works as a pre-crop for carrot and beetroot - two crops that are suitable for long-term storage, accepted and well-incorporated into the Swedish diet, and appropriate for direct human consumption.

At the study site in Lönnstorp research station (latitude 55.67°N 13.11°E), Kernza™ has been cropped for six years before the establishment of this study. On adjacent land, a crop rotation of conventional annual cereal crops has been managed simultaneously. Termination of both these fields by ploughing the top 10 cm took place in spring, and carrot and beetroot were sown 19 days later in both fields. Before the establishment of subsequent crops, during the growing season, and after harvest, measurements of several soil parameters took place: bulk density, pH, respiration, organic matter content through loss of ignition (LOI, %) and water content (WC, %). The subsequent crops were harvested in September and harvest weight and quality was measured, where the quality of crops was determined with help of the standards of organic small-scale farmers in Sweden. Results showed that most soil parameters measured (water content, organic matter content and respiration) was significantly higher for the plots where Kernza™ was grown earlier, however, the harvest amount and weight was much lower. Even though the plots following the annual crop cycle contained a higher weed biomass, less nitrogen, carbon, water and organic matter, the harvest of carrot and beetroot was higher here. This study tells us that more research is needed into the complex dynamics between management history and crop type. The contrasting results from this study are recognized among other researchers and may be a result of nutrient detention in root residues. Due to shallow ploughing, caused by mechanical resistance, root residues most likely remain in the soil. Changing termination timing of intermediate wheatgrass to earlier and later times has been done in regard to re-emergence of Kernza-tillers but can also be done with the purpose of following up on subsequent crop emergence and development. Incorporating perennial crops in what are normally annual crop cycles can be beneficial from many points of views, and there is a wide scope for future research.

Appendix 1

Method and materials

Soil water content, WC (%)

An exact quantity between 2 to 10 grams of sieved fresh soil from the soil core auger was added to a ceramic crucible of known weight and dried in a drying cabinet for twenty-four hours, in 105°C, before being weighed for the dry weight.

WC (%) was later calculated by the following equation:

$$WC (\%) = \frac{(\text{weight of fresh soil} \dagger - \text{weight of dry soil})}{(\text{dry weight} - \text{crucible weight})}$$

†) including crucible weight

Soil organic matter content, LOI (%)

All samples were placed in a Nabertherm B400 oven and burned for three hours at 550°C. Following, the samples were weighed to establish the loss of ignition, LOI (%).

The following equation was used to calculate LOI (%):

$$LOI (\%) = \frac{((\text{weight of dry soil} \dagger - \text{weight of ignited soil} \dagger))}{(\text{dry weight} - \text{crucible weight})} \times 100$$

†) including crucible weight

Soil pH

5 grams of fresh soil was derived from each sample, added with 10 millilitres of 0,2M KCl. The samples were shaken for one hour and left two hours to settle. The pH-value of the soil was measured calorimetrically.

Soil respiration

30 millilitres of sieved and air-dried soil from each plot were put into small beakers of known weight. The samples were weighed before adding 9 millilitres of deionized water to each beaker. Beakers were sealed shut and incubated in darkness for twenty-four hours before measurement.

The equation used to calculate the soil respiration was as follows:

$$\text{Respiration } \frac{(\text{ppm})}{\text{day}} = \frac{\text{PPM CO}^2\text{-C}}{\text{Bulk density (g)}}$$

Soil bulk density

Cylinders with a volume of 384,8451 cm³ were pressed into the soil at each plot (eighteen cylinders in total). The samples were positioned at random within each plot. The bulk density samples were transferred to aluminium trays for determination of the fresh weight and then dried in 105°C in a drying cabinet for twenty-four hours for determination of the dry weight. The soils were later homogenized and sieved through a strainer of 2 millimetres. The small and large fractions of the soil samples were weighed separately, and the bulk density was calculated by dividing the soil weight in grams by the volume of the cylinder.

Soil respiration

Samples collected using a soil core auger (three samples from each plot were collected to gather enough soil for testing) were sieved through a 2-millimeter strainer. 30 grams of each sample were placed on aluminium trays to air dry in room temperature.

Quantitative and qualitative assessments of harvest samples

Root weight and dry weight of leaves

Harvest samples were taken from all nine plots within both treatments (a total of eighteen plots). All plots contained four rows of either carrot or beetroot; a sample of 50 centimetres was taken from the third row of each plot. The harvest samples were washed, and the leaves were cut from the roots. The dry weight of the leaves was measured after drying in a drying cabinet for forty-eight hours. The roots of all samples were counted as well as weighed. No lower limit for qualification was set either for beetroots or carrots, however later assessments included separation and weighing of beets with a diameter smaller than 3,5 centimetres as well as carrots under 10 centimetres in length and 1,5 centimetres in diameter; this was done to determine the portion of “commercially approved” roots in each sample. These requirements were set to accommodate a selection process like that of organic and small-scale non-industrial farming systems in the local area. As carrots were graded both after length and diameter, a combined system for size classification was assembled. A carrot of the shortest grade length (10-15 cm) and the smallest diameter (1,5-4 cm) has been classified as ‘small’, while a carrot of the shortest grade length and the medium diameter (4-6 cm) has been classified as medium. That is to say, the higher size classes promote a higher combined size classification.

The samples were also visually scanned for damage or growth irregularities caused by either mechanical resistance, disease, or pests.

Appendix 2

Study site

The field areas in this study site were established from larger areas of perennial and annual cropping systems. The area where Kernza was terminated in 2021 to establish the perennial pre-crop treatment (treatment P) is 6 × 6 meters and located adjacent to an annual cropping system. In the annual cropping system, wheat was terminated in 2021 to create the annual pre-crop treatment (treatment A), where beets and carrots were sown later. Sowing date was 7th of June and both treatments were irrigated on the 14th and 23rd of June, during the seed emergence and crop establishment phase. Weeds were removed by hand in July on both the perennial and annual treatments after a visual estimation of weed species percentage cover was made. Kernza was terminated by rotary cultivator on 19th of May 2021 and the plot was rototilled again on June 3rd.

Table 4a.

This table shows the management history of the plots that have been used as experimental plots in this field study (field A has been used for the annual pre-crop treatment and field P has been used for the perennial pre-crop treatment).

Year	Field	N (kgN/ha)	Management	Harvest	Crop
2014	P	No fertilizer			Sowing of Kernza
	A	-			-
2015	P	60	Weeding	Threshing, baling (Sept)	Kernza
	A	139			Spring barley
2016	P	40		Threshing (Aug), baling (Sept)	Kernza
	A	110 (spring) + 60,5 (autumn)			Spring barley
2017	P	40		Threshing (Sept), baling (Nov) (delayed due to wet weather)	Kernza
	A	157			Winter rape seed
2018	P	No fertilizer		Threshing, baling (Aug)	Kernza
	A	159			
2019	P	60			Kernza
	A	108			Winter barley
2020	P	80			Kernza
	A	No fertilizer ¹			No crop
2021	P	No fertilizer	Rototilled twice		Beets & carrots
	A	No fertilizer	Rototilled twice		Beets & carrots

Management history

Kernza was sown on the 17th of September in 2014 at a depth of 1 cm, with 12,5 cm distance between rows and a sowing density of 16,7 kg/ha. The plot used for this study is a plot of 6 × 6 meters from the Kernza field. The Kernza field has since its establishment received less kgN/ha compared to the annual fields due to the general acceptance of Kernza as a more nutrient efficient crop, considering a deeper and denser root system and a longer period of growth. The application regime for kgN/ha (of different types of fertilizers, mostly NPK of varying ratios but also calcium nitrate with 15,5% N) between the years 2014 to 2021 on the perennial field with Kernza has been no fertilizer, 60, 40, 40, no fertilizer, 60, 80, no fertilizer, consecutively. For the same years for the annual fields, except 2014 where no data is available, the fertilizer regime has been 139, 110,4 (spring) and 60,45 (autumn), 157, 159, 108, no fertilizer (cultivated tread), and no fertilizer. The plot used for treatment A is also derived from a larger field, but with a history of annual crops. The plot established from the annual crop rotation was cultivated several times in 2020, ploughed in August of 2020, and harrowed twice during autumn. The field with Kernza has since the year after cropping been harvested both for seeds and for straw.

Field design

The fields used for this study are located at Lönnstorp research station (latitude 55.67°N 13.11°E), established from larger areas of perennial and annual cropping systems, respectively. The perennial and annual pre-crop plots are 6 by 6 meters, divided into nine internal plots, with three blocks. The perennial treatment contains 5 plots of beetroot, and 4 of carrots. The annual treatment contains 4 plots of beetroot and 5 plots of carrots. The placement of the carrot and beetroot plots within each treatment were randomized and contained less or more of one of the subsequent crops due to the uneven number of plots (see Figure 7 below).

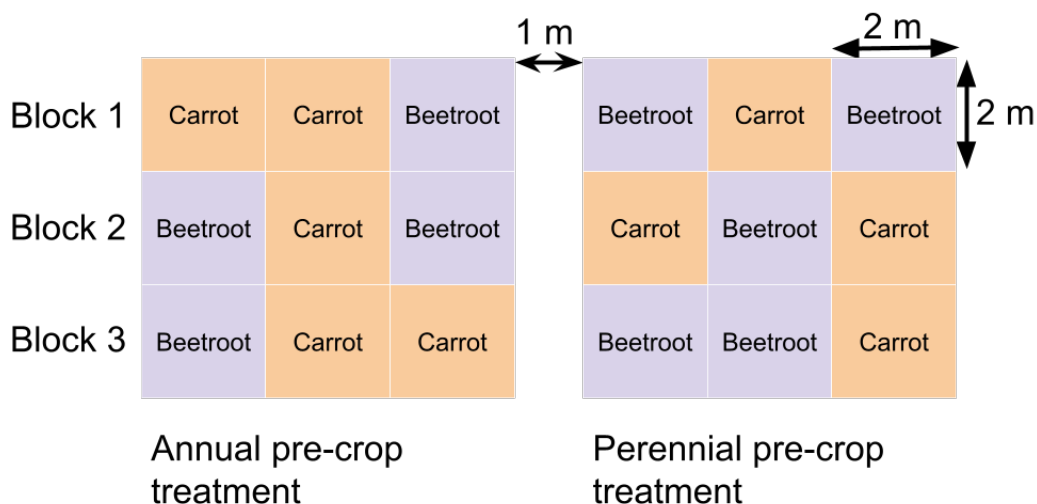


Figure 4a.

Field design showing the placement of the carrot and beetroot plots in the annual versus perennial pre-crop treatments. The treatments were separated by a 1 m untreated strip.

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