



Land conversion from annual to perennial crops: A win-win strategy for biomass yield and soil organic carbon and total nitrogen sequestration

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ABSTRACT

How much can we increase biomass yield by promoting land conversion from annual to perennial crops? Will increased biomass extraction for biorefineries reduce soil organic carbon (SOC) and total nitrogen (TN) stock? Which cropping system is more stable for biomass production over time? To our knowledge, no study has concurrently investigated the effects of land conversion from annual to perennial crops on biomass yield, yield stability, and changes in SOC and TN stock, which limits the understanding and application of sustainable agroecosystems producing biomass for biorefineries. Based on five-year continuous observations in central Jutland Denmark, our results showed that perennial crops significantly increased biomass yield by 19% and yield stability by 88% compared to annual crops. Perennial crops significantly increased SOC content by 4% and SOC stock by 11% at 0–100 cm depth across the five years. The opposite responses of SOC content and stock under annual and perennial crops led to even more significant differences between the crop types. Perennial crops had no effect on soil TN content and increased soil TN stock to one meter depth by 22%, whereas continuous annual crops had no effect on it. Neither annual nor perennial crops had effects on SOC and TN stock when estimated based on equivalent soil mass because the soil density increased under perennial crops. Our results showed that changes in SOC and TN stock between annual and perennial crops varied with the specific calculating methods (fixed depth/equivalent mass), thus the selected methods should be clearly defined in the future research. Increases in SOC content at one meter depth were positively correlated with biomass yield and yield stability, suggesting a win-win strategy for climate mitigation and food security. Altogether, our results highlight the potential to redesign the current cropping system for sustainable intensification by selecting proper perennial crops for green biorefineries.

1. Introduction

With the rapid growing of world population to nearly 10 billion by 2050, global demands on agricultural products for food, materials and bioenergy will at least be doubled compared to 2005 levels, which requires much higher biomass yield per unit farmland area (Gelfand et al., 2013; Sheldon, 2014). Meanwhile, to combat the accelerated climate change and increase soil quality, there are growing needs to increase soil organic matter content in agricultural systems (Lal, 2004; Don et al., 2012; Plaza-Bonilla et al., 2015; Sun et al., 2021). Therefore, innovative cropping systems and cropping managements that can sustainably increase biomass yield for biorefining are highly required (Pugesgaard et al., 2015; Chen et al., 2020). Some studies are advocating that

perennial crops are potentially the most promising bioenergy crops because of their large biomass yield, deep root distribution, high resource use efficiency and long growing season (Adler et al., 2007; Asbjørnsen et al., 2014; McGowan et al., 2019). However, many of these studies on perennial crops are primarily focused on either biomass yield or absolute changes in soil organic carbon (SOC) and total nitrogen (TN) stock, resulting in biomass yield and SOC and TN stock being largely investigated independently.

Apart from biomass yield and SOC and TN stock, temporal yield stability is another important variable that is insufficiently considered between annual and perennial crops. Yield stability is a concept that is primarily developed from conventional ecology, which has just recently been introduced to agroecosystems (Becker and Léon, 1988; Knapp and

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van der Heijden, 2018). Yield stability denotes the year-to-year variability in biomass yield across a certain time. Higher yield stability shows that the studied cropping system can better adapt to environmental stresses and changing climate (Knapp and van der Heijden, 2018). To our best knowledge, there is no studies that have systematically compared annual and perennial crops with respect to biomass yield, yield stability, changes in SOC and TN stock, as well as the relationships between them in the same experimental platform.

2. Materials and methods

2.1. Study site

In 2012, we established an experimental platform at Aarhus University Foulum (9°35' E, 56°30' N, 48 m a.s.l.) to systematically compare the effects of annual and perennial crops on biomass yield for bio-refineries and SOC and TN stock. Based on the long-term meteorology records (Fig. S1), the mean annual temperature was 7.8 °C, the mean annual precipitation was 740 mm, and the mean annual potential evapotranspiration was 600 mm. The soil was classified as Typic Hapludult with a sandy loam texture (8% clay, 11% silt, and 78% sand). Soil pH was 6.5 and soil bulk density (SBD) was 1.2 g cm⁻³. Detailed information about the study site can be found in Chen et al. (2020) and Manevski et al. (2017).

2.2. Experimental design and soil sampling

Detailed information on experimental design, crop managements, harvesting for biomass yield, soil sampling, SBD, and SOC and TN stock calculation can be found in the [supplementary information](#). In brief, two conventional annual crops (*Zea mays* and *Triticosecale*) and four perennial crops (*Festuca arundinacea* Schreb., *Festulolium pabulare*, *Phalaris arundinacea* L., and *Dactylis glomerata* D.) were separately planted in each plot following an incomplete split-plot design with four replicates and simultaneously compared in the same experimental platform. Sowing date, seeding rate, irrigation, pesticide, fertilization, and harvest date followed Danish agro-legislation and -advice, and detailed information is shown in [Tables S1 and S2](#). All aboveground biomass was harvested once per year for annual crops using a combine harvester (Haldrup C-65, Ilshofen, Germany), while it was harvested 2–4 times per year for perennial crops depending on species and the specific growth conditions. Nutrients were fertilized after each harvest for perennial crops to stimulate plant regrowth, while the fertilization for annual crops is listed in [Tables S1 and S2](#). Eight soil samples were collected to one meter depth and mixed for one soil sample from different layers for each plot in both 2012 and 2017. Soil bulk density was documented by sampling undisturbed soil cores after removing stones larger than 2 mm. SOC and TN content were analyzed by dry combustion using a Vario MAX cube (Elementar Analysensysteme AG, Langenselbold, Germany).

2.3. Data analysis

Yield stability was calculated based on the reciprocal coefficient of variation of biomass yield from 2013 to 2017 (Smith et al., 2007; Knapp and van der Heijden, 2018). When comparing the mean values, data was firstly averaged by annual and perennial crops within each block. To explore the overall differences between annual and perennial crops, linear mixed effects models were adopted. All variables were tested for normality before statistical analysis and log-transformed when necessary. We set annual/perennial crops, year, and their interactive effects as fixed effects, while considering each block as random factors. Tukey's post hoc tests were used to explore pairwise comparisons. Significant differences were separately evaluated at $p < 0.05$. Mixed regression analysis was adopted to explore the relationships between averaged biomass yield, yield stability and changes in SOC and TN stock across the five years, in which block were considered as random factors. Residuals

were examined for normality and the residual variances were examined for homogeneity for all models.

3. Results

Averaged across the five years, perennial crops increased biomass yield by 19% ($p = 0.03$, Fig. 1 A, Table S3) compared to annual crops. There were significant year effects and significant interactive effects of year and crop species on biomass yield ($p = 0.01$). We thus separately calculated the differences for each year. Specifically, perennial crops had 10% ($p = 0.05$), 8% ($p = 0.01$), 27% ($p < 0.01$), 15% ($p = 0.04$), and 47% ($p < 0.01$) higher biomass yield than annual crops in 2013, 2014, 2015, 2016, and 2017, respectively (Fig. 1C). In addition, perennial crops also enhanced yield stability by 88% compared to annual crops ($p = 0.01$, Fig. 1B).

Compared to the soil samples collected before the experiment establishment in 2012, perennial crops significantly increased SOC content by 4% ($p < 0.01$, Fig. 2 A and Table S4) and continuous annual crop had no effect on it across the five years. There were significant differences for changes in SOC content between annual and perennial crops ($p = 0.02$). Both annual and perennial crops had no effects on soil TN content (Fig. 2B). Regarding SOC and TN stock at 0–100 cm depth, perennial crops significantly increased SOC stock by 11% ($p = 0.05$, Fig. 2 C and Table S5) and continuous annual crops had negative but statistically non-significant effects on it across the five years. The divergent responses of SOC stock led to significant differences of changes in SOC stock between annual and perennial crops ($p = 0.04$, Fig. 2 C). Regarding soil TN stock, five-year continuous annual crops had no effect on it, whereas perennial crops increased it by 22% ($p < 0.01$, Fig. 2D). Based on equivalent soil mass, however, both annual and perennial crops had no effects on SOC and TN stock and there was no significant difference for changes in equivalent mass SOC and TN stock between annual and perennial crops (Fig. 2E and F; Table S6).

4. Discussion

Our results highlight the potential to increase biomass yield and yield stability, while increasing SOC and TN stock by promoting land conversion from annual to perennial crops. However, new crops are only of interest if they can fit into societal and market demands for raw materials or products. Our experimental platform was dedicatedly designed to explore how much biomass yield can be produced for bio-refining by introducing proper perennial crops (Chen et al., 2020). Biomass yield decreased with year for both annual and perennial crops. The annual crops were grown in continuous monoculture, which is known to induce risks of soil-borne diseases (Arafat et al., 2019), while it is usual to see a maximum yield in perennial fodder-grasses in year 1–2, after which there is a decline over time (Eriksen et al., 2004). The lower biomass yield for annual crops in 2017 was due to a severe yellow rust infection in triticale, while the generally higher biomass yield in 2014 might be due to the well matched relative high temperature and rainfall during the growing season (Fig. S1). Nevertheless, our results provide at least early evidence that biomass yield, yield stability, and SOC and TN stock can be simultaneously increased by selecting proper perennial crops with optimized crop managements.

Five explanations may account for the increased biomass yield, yield stability, and SOC and TN stock when changing annual to perennial crops. First, perennial crops intercept more solar radiation across the growing season than annual crops where part of the season is used for germination, maturation, harvest and reseeded (Manevski et al., 2017). Second, the selected perennial crops are reported to have deep root systems, which will help them adapting to environmental stresses (e.g., flood and drought) (Norton et al., 2016; Cougnon et al., 2017). Third, the permanent deep root system and the large amount of root biomass associated with perennial crops may enable them to secure more nutrients and enhance SOC and TN sequestration, especially from deep

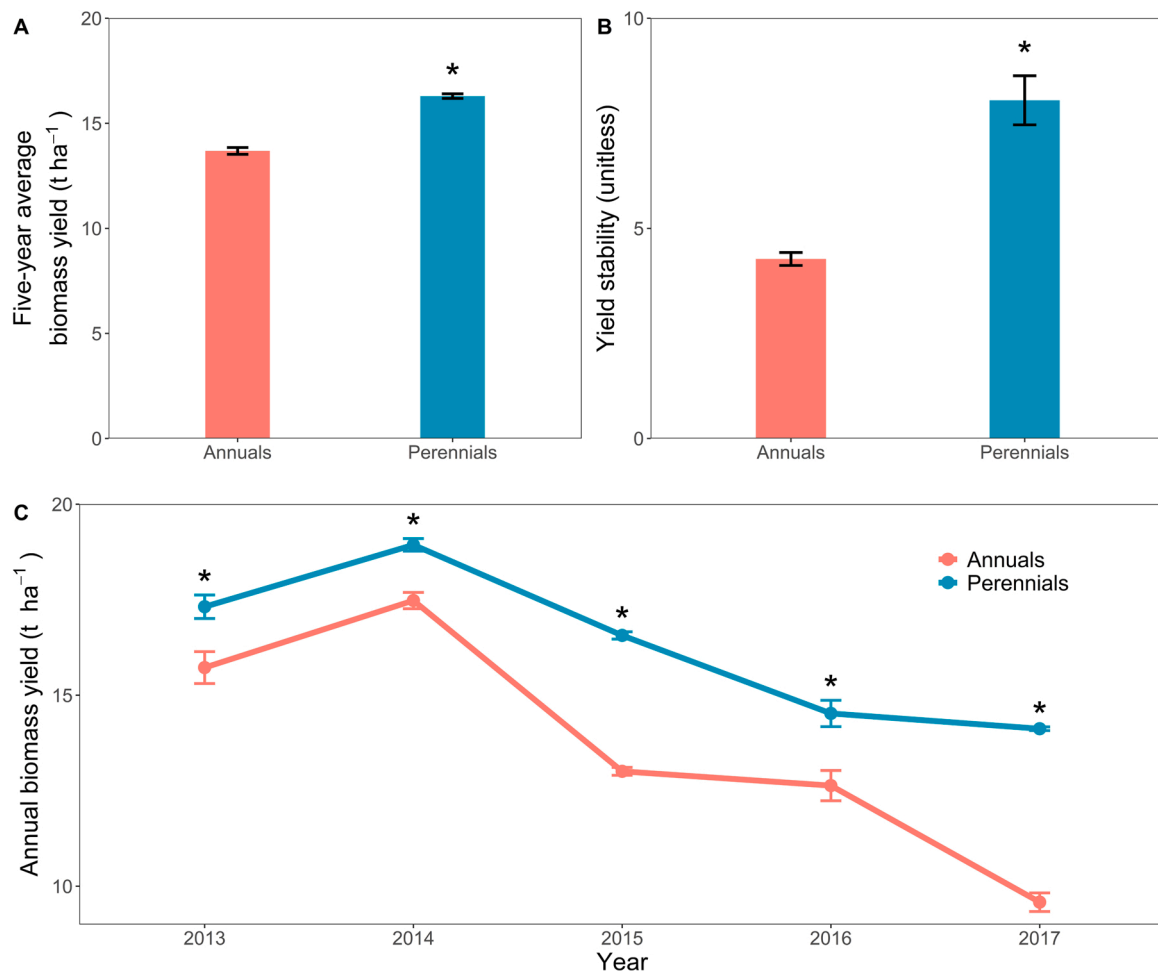


Fig. 1. (A) Five-year average biomass yield and (B) yield stability from annual and perennial crops across the five year. (C) Annual biomass yield from annual and perennial crops from 2013 to 2017. Asterisks above the error bars show the significant differences between annual and perennial crops. Significant differences were evaluated at $p < 0.05$. Linear mixed-effects models were conducted. Different cropping systems was considered as fixed factor, while block was considered as random factor.

layers (Thorup-Kristensen et al., 2020). For example, McGowan et al. (2019) reported that the perennial crops switchgrass and miscanthus significantly increased SOC stock by 0.8 and 1.3 Mg ha⁻¹ yr⁻¹, which were correlated with their larger root biomass, whereas continuous annual crops did not increase SOC stock. Fourth, perennial crops are reported to allocate more resources belowground, which will fuel microbial metabolic activities to facilitate plant growth and increase pest resistance, for example, by synthesizing extracellular enzymes (Kirk et al., 2005; Thorup-Kristensen et al., 2020). Last, we aimed at balancing fertilisation with nutrients removed by harvest for all the crops in our study site. The perennial crops received higher fertiliser inputs compared to the annual crops because these perennial crops were harvested green 2–4 times per year. The higher fertiliser inputs may potentially contribute to the larger SOC and TN stock (Chen et al., 2017, 2018; Wang et al., 2019; Li et al., 2022), but further research on nitrogen balance is required. Unfortunately, as far as we know, these five potential mechanisms are not adequately examined in the same experimental platform, hindering the mechanistic understanding and application of perennial crops in a broader context.

Our results indicated that increases in SOC stock at one meter depth with perennial crops can be positively associated with biomass yield and yield stability (Fig. S2). We propose three possible hypotheses to guide future research. First, the nature of the selected perennial crops (e.g. long growing season, deep root, high pest resistance) must ensure their adaptation to the climatic and edaphic conditions at the specific study

site, which provide prerequisite conditions for high biomass yield, yield stability and SOC sequestration. Second, enhanced SOC stock could improve soil physiochemical properties, for example, soil aggregation and porosity (Yagüe et al., 2016), nutrient turnover, cation exchange capacity (Tiessen et al., 1994), moisture retention and availability (Jiang et al., 2019). Changes in these physiochemical properties are reported to have direct or indirect positive effects on biomass yield and yield stability (Hatfield et al., 2011; Knapp and van der Heijden, 2018). Third, high SOC stock could enhance soil food web stability and support soil organisms' diversity (Tsiafouli et al., 2015). Relative high soil organisms' diversity and relative stable soil food web will increase ecosystems' resilience to other unexpected biotic and abiotic stresses (Steinbeiss et al., 2008; Hartmann et al., 2015). Altogether, our results suggest that increased SOC stock will not only contribute to the climate mitigation but may also increase biomass yield and yield stability in the long term.

The effects of annual and perennial crops on SOC and TN depend on the specific calculation methods used. The changes observed on SOC and TN stocks at one meter depth in this study were a little larger than those from other studies based on equivalent mass method (Don et al., 2012; Ferchaud et al., 2016). At this standpoint, cautions are required when evaluating changes in SOC and TN stock, although SOC and TN stock at fixed soil depth is the commonly used method. Second, the initial SOC and TN content was a little lower in plots with perennial than annual crops due to soil heterogeneity, which might have contributed to the

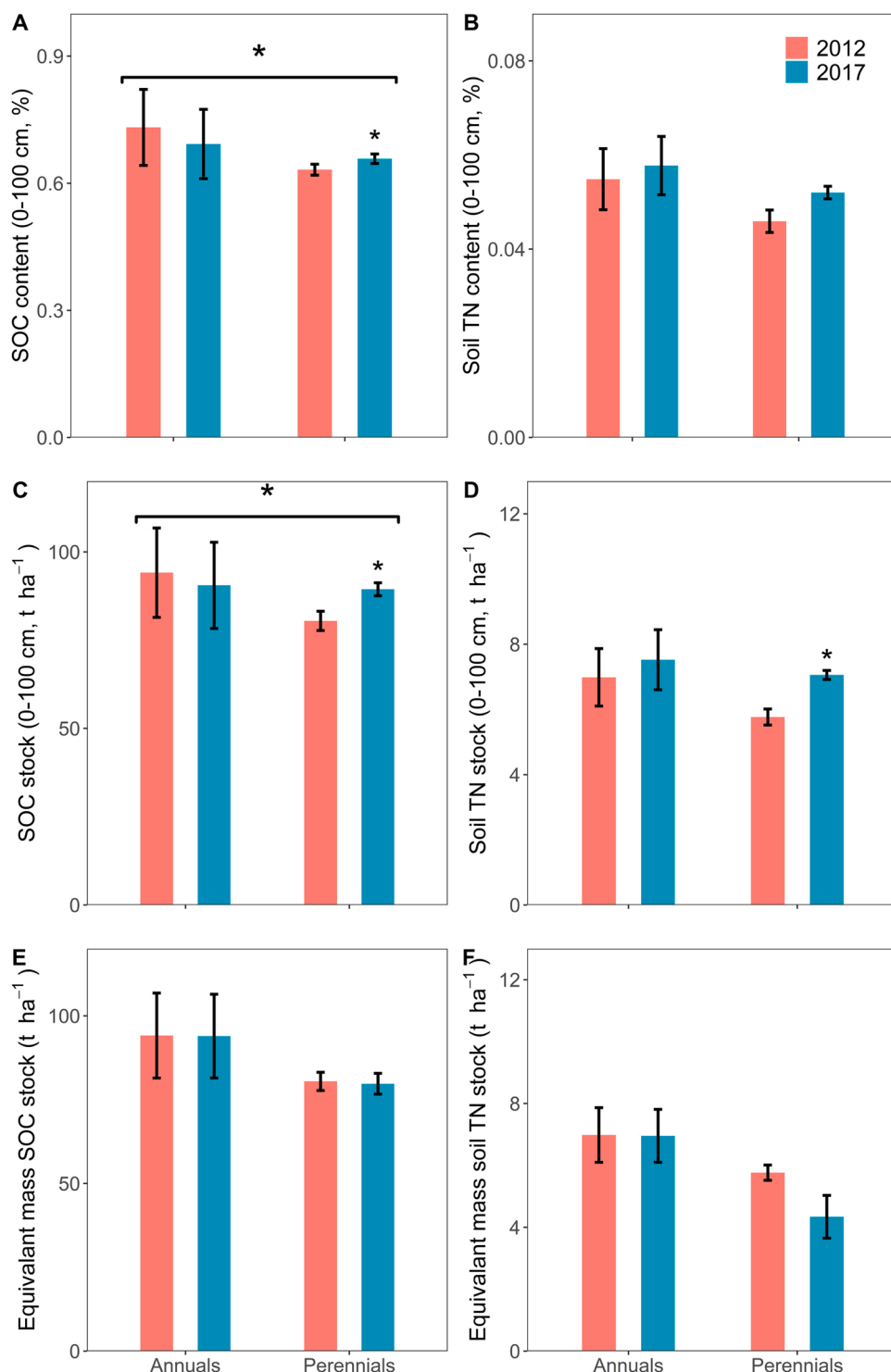


Fig. 2. Soil (A) organic carbon (SOC) and (B) total nitrogen (TN) content at 0–100 cm depth, (C) SOC and (D) TN stock at 0–100 cm depth, and equivalent mass (E) SOC and (F) TN stock for annual and perennial crops across the five years. Asterisks above the error bars show the significant differences between 2012 and 2017. Asterisks above the brackets show the significant differences of the change between annual and perennial crops from 2012 to 2017. Significant differences were evaluated at $p < 0.05$. Linear mixed-effects models were conducted. Cropping systems was considered as fixed factor, while block was considered as random factor. Detailed statistical results are shown in Tables S4–S6.

significant increase in SOC and TN content with perennial crops. However, there is no significant difference for the initial SOC and TN content between annual and perennial crops, which may to some extent help rule out this uncertainty. Third, the perennial crops were carefully selected based on their growth performance in the humid and temperate Nordic region. Therefore, cautions are required when comparing and interpreting our results with species in other pedoclimatic regions or with other crop managements.

5. Conclusion

Our results clearly showed that the selected perennial crops under optimal managements (e.g. balanced application of fertiliser) can significantly increase biomass yield and yield stability compared to continuous annual crops. Across the five years, perennial crops significantly increased SOC content and stock at one meter depth, but the effects on equivalent mass SOC stock were non-significant. Perennial crops also increased soil TN content but had no significant effect on either soil TN stock at 0–100 cm depth or equivalent mass soil TN stock. In

addition, continuous annual crops had no effect on SOC and TN, regardless the evaluating method. These results highlight the differences of various SOC and TN evaluation methods and the necessity to optimise the soil sampling method accordingly. The differential responses of SOC content and stock at one meter depth to annual and perennial crops led to a more evident increase in SOC content and stock with perennial crops when compared with the continuous cultivation of annual crops. Therefore, we highlight the importance to simultaneously compare annual and perennial crops at a given site rather than to investigate the absolute effects of perennial crops over time, which may underestimate the benefits of land conversion from annual to perennial crops on SOC stock. Furthermore, increase in SOC stock to one meter depth by cultivation of perennial crops was positively correlated with biomass yield and yield stability. Taken together, perennial crops can potentially be a win-win strategy to combat the dual challenges of globally increasing demands on biomass yield and needs for climate change mitigation.

CRedit authorship contribution statement

JC, PEL and UJ designed the study and collected the data. JC led the data analysis, data interpretation and writing with contributions from all co-authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2022.107907](https://doi.org/10.1016/j.agee.2022.107907).

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