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Deliverable 1.2. Report and publication on model comparisons and identification of model linking soil carbon to soil properties and crop productivity

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Report and publication on model comparisons and identification of model linking soil carbon to soil properties and crop productivity

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Executive summary

This deliverable reports – in the form of a manuscript in preparation – the efforts towards identifying and applying a modeling approach that can link soil carbon to soil properties and further assess the effects of these properties on crop productivity. The work was made within Task 1.2 of WP1 of the SmartSOIL project.

No current simulation models are able to directly simulate crop yield responses to changes in soil C management. More specifically, models fail to link crop yield to changes in soil structure as well as SOM turnover effects on soil mineral N, so a new approach of linking soil carbon to soil properties and crop productivity was needed. A new combined modelling approach was identified by merging a crop growth model with a number of pedotransfer models. The crop growth model (Daisy) was combined with four different available pedotransfer functions (PTFs) developed from different European soil datasets. The effects on crop productivity of varying SOC, using different PTFs, were tested by running scenarios with the Daisy model for a range of years including both wet and dry growing seasons.

The results of the PTF model comparison and the combined model scenarios are detailed in this report in the manuscript in preparation entitled “Simulation of crop yield responses to varying soil properties and functions as affected by long-term carbon management”.
The main results of the analyses were that 1) four different PTFs showed similar relative changes in plant available water for varying SOC and 2) for a Northern European site with few seasons with soil water stress limiting crop growth, there seemed to be no effect on maximum crop yields at high fertilizer N inputs of a moderate change in SOC, e.g. as a consequence of soil management. For lower N inputs, crop yields varied according to SOC so higher yields were obtained for the case when SOC was increased by 50% compared to the reference scenario.
For the final version of the manuscript, the scenarios will be complemented by scenarios representing a drier Southern European climate (Italy).

Simulation of crop yield responses to varying soil properties and functions as affected by long-term carbon management

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Abstract

Soil Organic Matter (SOM) is a source of essential nutrients for plant growth and energy source for microbial population and its depletion causes adverse climatic affects by releasing CO_2. We investigated the benefits of soil organic carbon (SOC) on winter wheat productivity by simulating soils with three different SOC levels (2%: High; 1.3%: reference and 0.7%: low) at 7 nitrogen rates (0-300 kg N ha^{-1}) with the plant-soil atmosphere system model Daisy. At high SOC, the grain (2.74 Mg ha^{-1}) and above ground biomass (5.94 Mg ha^{-1}) yield was projected to be 2 times higher compared to low SOC. Similarly, the mean root density was 1.08, 0.87 and 0.62 cm cm^{-3} soil at high, reference and low SOC, respectively. Differential effects of SOC was recorded over the depth of the soil profile, with higher root density in high SOC contents in the upper soil compartment and this SOC effect diminished down the soil profile until no difference was seen at 120 cm soil depth. SOC and soil water content was highly correlated, with high SOC retaining 30-32 mm and 13-14 mm more soil water compared to low SOC and reference SOC, respectively. The retention curve difference between high and low SOC ranged between 1- 3% of water holding capacity in pF range 0-4.2, whereas the difference between high and reference SOC ranged between 1-2% of water holding capacity. The higher grain and aboveground biomass yields were attributed to enhanced availability of soil water, plant nutrients and higher root biomass for uptake resulting in enhanced crop productivity. The study demonstrated that SOC has significant effects on crop productivity, which underlines the need to increase SOC contents to maintain the productive capacity of soil in addition to mitigating climate change.

1. Introduction

Soil carbon supports multiple functions determining the soil physical, chemical and biological quality parameters (Pan et al., 2009,Reeves, 1997) contributing to the productive capacity of soils for food, fodder and energy production (Lal, 2004). Soil carbon consists of two components; soil inorganic carbon (SIC) and soil organic carbon (SOC) (Mishra et al., 2010). SOC is the major constituent of soil organic matter (SOM), commonly used as an indicator of soil quality (Tornquist et al., 2009). The SOC pool constitutes the largest component (1500 Gt C) in the biosphere; three times the terrestrial biomass pool and two times the atmospheric pool (Lal, 2008). SOM is a reservoir of major and minor plant nutrients, responsible for soil aggregation for improved soil tillage and reduced soil erosion. It provides an energy source for soil biota, enhances crop yields and buffers greenhouse gas (GHG) emissions from soil to the atmosphere (Lal, 2004). A number of factors influence the SOC stock, spatially and temporally, in an ecosystem due to management, climate, terrestrial vegetation, soil mineralogy and the interactions between these factors (Canadell et al., 2007). Past inventories of SOC have demonstrated that the practice of clearing vegetation for agriculture has steadily increased the CO2 emission and other GHG (CH4 and N2O) concentration in the atmosphere, contributing to global warming (Lal, 2003). Research into various factors affecting GHG emissions have identified that land use pattern, soil management and cropping systems have a significant role to play (Bernoux et al., 2006). Land use change is estimated to contribute 135±55 Pg C due to decomposition of vegetation and mineralization of humus or SOC during the period 1850-1998 (Smith et al., 2008a). Adoption of recommended management practices (RMP) like minimum-tillage, manure and compost use, crop residue incorporation, improved crop rotation with incorporation of grassland/sward, cover crop and deep-rooted crops, fertilizer and irrigation application can help restore SOC pool by net gain of atmospheric CO2 into the soil (Smith et al., 2008b).

European arable cropping systems are net contributors of CO2 and are estimated to lose 300 Mg SOC year-1 (Janssens et al., 2003). With RMPs, SOC sequestration to the tune of 90-120 Mg SOC year-1 can be achieved in arable production systems (Smith, 2004). With 20% reduction target in GHG emissions by 2020 compared to 1990 levels in Europe, arable production systems can be a potential area for intervention to sequester carbon (www.eea.europa.eu/accessed on 21.10.2010). SOC sequestration rates are influenced by soil mineralogy, climate, moisture availability, crop residue quality etc. and their interactions. To assess the long-term management effects on SOC, models are used to keep track of multiple plant and soil factors and their interactions affecting SOC dynamics. In this study, a soil-plant-atmosphere model, Daisy, was used. The objective of the study was to investigate how three levels of SOC viz. 2.0% (high), 1.3% (reference) and 0.7% (low) impacts upon grain yield, aboveground biomass, root density, soil water and the moisture retention curve.

2. Materials and Methods

2.1 Study site characterisation

2.1.1 Soil properties

The long term trial site in Askov (LTE-Askov) has been under cultivation since 1894 before which the land was characterised by open space, heathland, grassland and shrubs (Christensen et al., 2006). The trial site is designated as 'Lermark' B3 (trial manager's identification of the site) with a sandy loam soil; the soil physical and chemical characteristics at the start of the trial are provided in Table 1. Lermark B3 has been managed with 4-year crop rotation cycle of winter cereal, root crop, spring cereal and grass-clover since 1923. During 1923-1949, the winter cereal was either winter rye or winter wheat and the spring cereal was oat or barley (LTE database). Since 1949, the winter cereal has been winter wheat and spring cereal has been spring barley. Lermark B3 treatments are different quantities of animal manure (AM) (0.5, 1, 1.5 AM) and nitrogen (N), phosphorus (P) and potassium (K) (0.5, 1, 1.5 NPK) and unmanured plots. Among those, data from unmanured and 1.5 NPK plots were used in this study for calibration of the model. Unmanured plots are managed with no FYM and NPK and crop residues were removed, whereas the 1.5 NPK plots received 102-22-86 kg NPK ha-1 (1923-1950), 105-24-99 kg NPK ha-1 (1951-1974), 150-28-131 kg NPK ha-1 (1975-2006), 225-45-180 kg NPK ha-1 (2007-2011) (LTE database).

Table 1
Physical and chemical soil characteristics of LTE-Askov at the start of the experiment.

Soil depth (cm)	Silt (%)	Clay (%)	Fine sand (%)	Coarse sand (%)	SOC %	Bulk density (g cm^{-3})
0-20	13	11	43	35	1.3	1.50
20-50	12	11	40	37	0.8	1.55
50-100	13	21	36	31	0.2	1.60
100-200	14	22	35	29	0.1	1.70

Source (Christensen et al., 2006)

2.1.2 Weather data

Weather data (1970-2011) was generated by LARS-WG 5(Semenov et al., 2002) based on statistical characteristics of actual samples of available weather data from LTE-Askov. LARS-WG is a stochastic weather generator which uses a statistical model to generate site parameters, which in turn is used to generate synthetic daily weather data viz. mean temperature, precipitation, global radiation and evapotranspiration at a single site of interest based on the latitude, longitude and elevation information (Semenov and Stratonovitch, 2010). Mean temperature is based on the maximum and minimum temperature, depending on the wet and dry season. Precipitation is generated on the basis of wet and dry days and global radiation is based on the empirical distribution of dry and wet days.

2.1.3 Model validation

The model validation was carried out with winter wheat data from the long term experiments in Padova (LTE-Padova). For validation, the soil, weather and management data of LTE-Askov in the model were replaced with LTE-Padova and the simulated soil C, N, grain yield, aboveground biomass and harvest index simulation outputs were compared with measured LTE-Padova by MODEVAL 2.0 (Smith et al., 1997a). The result of model validation with MODEVAL 2.0 with winter wheat grain yield data is provided here for illustration (Fig.1). Different quantitative parameters were used to assess the accuracy of simulation compared to measured data. The goodness-of-fit (LOFIT), relative error (E), mean difference (M) and root mean square error were found to be within 95% confidence limit, which provided evidence of robustness of the model for simulation to be used in other climatic zones with corresponding management and soil information.

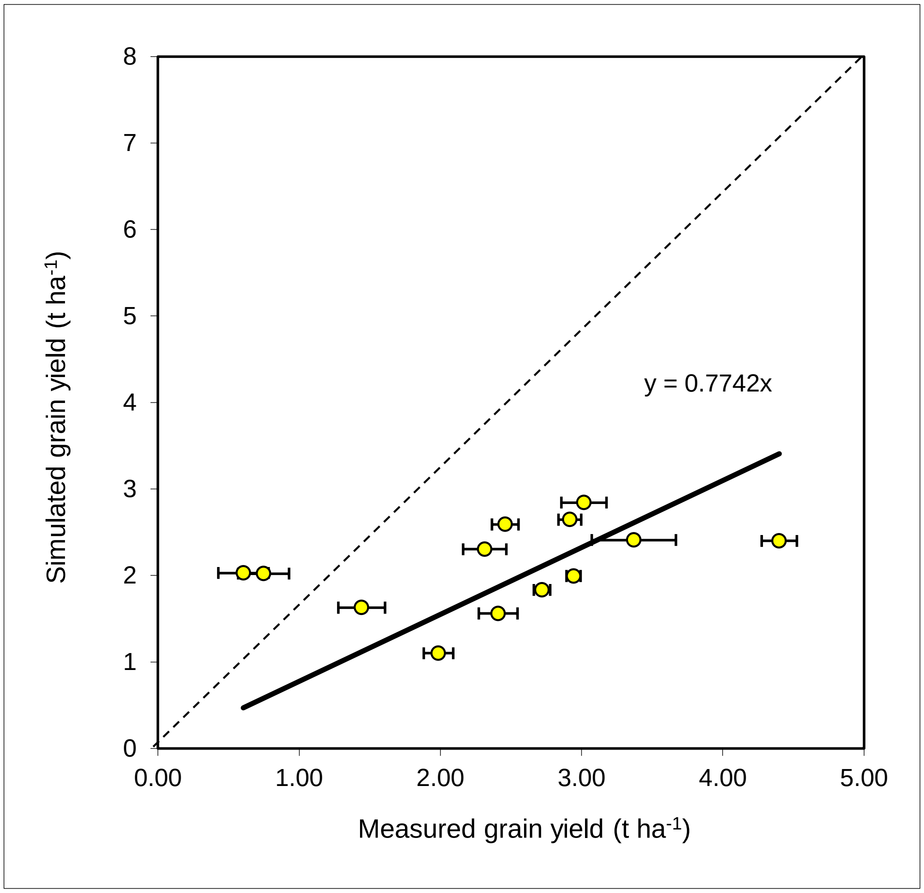


Fig 1: Model validation with LTE-Padova with no NPK and crop residues removed

2.2 SOC dynamics in the Daisy model

Daisy is a dynamic and deterministic soil-plant-atmosphere system model with separate sub-models for crop growth, C and N dynamics, heat, soil water and fate of pesticide use (Abrahamsen and Hansen, 2000). In Daisy model SOC is a sum of added organic matter (AOM), soil microbial biomass (SMB) and soil organic matter (SOM) pool. AOM and SMB constitute relatively fast and slow turnover pools, whereas SOM constitutes three pools; inert (SOM3), fast (SOM2) and slow turnover pools (SOM1), characterised by fixed C:N ratios and first-order decomposition rate coefficients (Hansen et al., 2012). AOM constitutes plant residues, added organic fertilizer or compost etc; the SMB pool is responsible for the biodegradation process and SOM is the recalcitrant humus fraction. Soil C and N dynamics were modelled by assuming constant C:N ratios in each pool (Bruun et al., 2003). The SOC pool, at the start of the simulation period, is dependent on the management during the pre-experimental period and the model was initialized by simulating the pre-experimental period for 10 years before the onset of the experiment (Bruun and Jensen, 2002).

2.3 Model initialization and calibration

The pre-experimental status of 1.3% SOC at 0-20 cm was considered as the reference SOC value. The 0-200 cm soil profile and SOC data including clay, silt, coarse and fine sand, bulk density from LTE-Askov (Table 1) was entered as input into the model. Model input requires humus % and SOC was converted to humus % based on the generic relationship (humus % = 1.72 × SOC %). For hydraulic characteristics, we used HYPRES continuous pedotransfer functions, which are based on 5521 soil horizon information available within Europe (Wösten et al., 1998). Different hydraulic parameters (θs, α, n, l and Ks) were derived from simple measurements of clay%, silt %, organic matter % and bulk density of corresponding soil profile (Wösten et al., 2001). The drainage consisted of pipes laid 18 m apart with horizontal distance of 9 m at 1.1 m in the soil profile. The rooting depth was set to 1.2 m and the initial SOC and background mineralization is based on the simulation output of the 10 years of pre-experimental period. The management practice of winter wheat was applied and sowing was done on 20th September, followed by N fertilizer application on 15th March and harvested by 20th August. 7 nitrogen treatments of 0, 50, 100, 150, 200, 250 and 300 kg N ha-1 were applied and the simulation was run separately for each N treatment for the period 1970-2011. Each simulation run sequence consisted firstly of 10 years of pre-experimental period with standard N application of 168 kg N ha-1 in winter wheat, followed by one of the N treatments (0-300 kg N ha-1) on 11th year, and on 12th year, the same cycle was repeated until end of the simulation period. In this way, 3 replicates of data on grain yield, aboveground biomass, root biomass, soil water and moisture retention curve were derived from each N treatment run from 1970-2011. Field data on aboveground crop grain and biomass yield and below-ground SOC dynamics at reference SOC were matched to the simulation outputs.

Two additional SOC scenarios were generated, where reference SOC was either halved (0.7% SOC or low) or doubled (2.0% SOC or high) on the basis of 0-20cm SOC content and the same method was applied down to 200 cm soil profile. On changing the values of SOC, corresponding changes in bulk density was calculated using a function derived from the LTE-Askov data [bulk density = 1.5209x-0.043 ($R^2 = 0.93$) where x = SOC %]. The simulation was then repeated for low and high SOC at 7 nitrogen application rates.

The relationship between SOC and plant available water content was determined by van Genuchten (vG) function. Literature search on pedotransfer functions (PTFs) identified 4 PTFs, with SOM as a variable to work out vG hydraulic parameters (θr, θs, α, n). The 4 PTFs used were: Hypres, rawls, schaap and Danish(ref!!!!) and the generated hydraulic parmaeters were used in vG function to work out soil water content at different soil water potential (pF). We defined field capacity at h = 100 cm and wilting point at h = 16000 cm and the difference of soil water content between the field capacity and the wilting point was taken as plant available water. Hydraulic vG paramters were calculated with low (scenario 1), reference (scenario 2) and high (scenario 3) SOM contents to establish the relationship between SOM and soil water content and the same procedure was followed for Askov and Padova soils.

2.4 Statistics

Winter wheat grain and aboveground biomass accumulation, root density, soil water content and moisture retention curve was compared between low, reference and high SOC. ANOVA tests were run in MS excel to assess the main SOC and N effects and SOC × N interaction effects. Significant effects are denoted as $p < 0.001$ ***, $p < 0.01$ **, $p < 0.05$*, ns = non-significant

3. Results

SOC effects were significant for winter wheat grain yield, aboveground biomass accumulation, soil water content, moisture retention curve and root density (Table 1) whereas N and SOC×N effects were significant for grain yield and aboveground biomass accumulation. N effects were also significant for root density (Table 1).

Table 1
ANOVA of SOC, N and SOC×N effects on winter wheat grain yield, aboveground biomass accumulation, soil water content, moisture retention curve and root density.

Factors	Grain yield	Aboveground biomass	Soil water content	Water retention curve	Root density
SOC	***	***	*	***	***
N	***	***	ns	ns	***
SOC×N	**	**	ns	ns	ns

SOC and N effects on winter wheat grain yield and aboveground biomass accumulation

The SOC effects (low, reference and high SOC content) on winter wheat grain and aboveground biomass accumulation were recorded until 200 kg N ha^{-1} application after which no effects were recorded. At 0 kg N ha^{-1}, the winter wheat grain yield increased by 2 times from low to high SOC content from 1.37- 2.74 Mg ha^{-1} (Table 2) and the grain yield increase with higher SOC, decreased with increasing N rate (Fig. 2) until no effects were recorded at 200 kg N ha^{-1}. Similar SOC effects were seen for aboveground biomass accumulation. At 0 kg N ha^{-1}, the winter wheat aboveground accumulation increased by 2 times from low to high SOC content from 3.09 - 5.94 Mg ha^{-1} (Table 3) and the biomass accumulation increase with increasing SOC, decreased with increasing N dose (Fig. 3) until no effects were recorded at 200 kg N ha^{-1}.

Table 2: SOC, N and SOC×N effects on winter wheat grain yield

N rate/SOC	2.0% SOC	1.3% SOC	0.7% SOC
Kg ha^{-1}	Mg ha^{-1}		
0	2.74	2.08	1.37
50	3.98	3.13	2.27
100	6.10	5.30	4.13
150	6.67	6.67	6.06
200	6.67	6.67	6.67

Table 3: SOC, N and SOC×N effects on aboveground winter wheat biomass accumulation

N rate/SOC	2.0% SOC	1.3% SOC	0.7% SOC
Kg N ha^{-1}	Mg ha^{-1}		
0	5.94	4.62	3.09
50	9.64	8.26	6.55
100	12.20	11.35	10.03
150	12.80	12.80	12.16
200	12.80	12.80	12.80

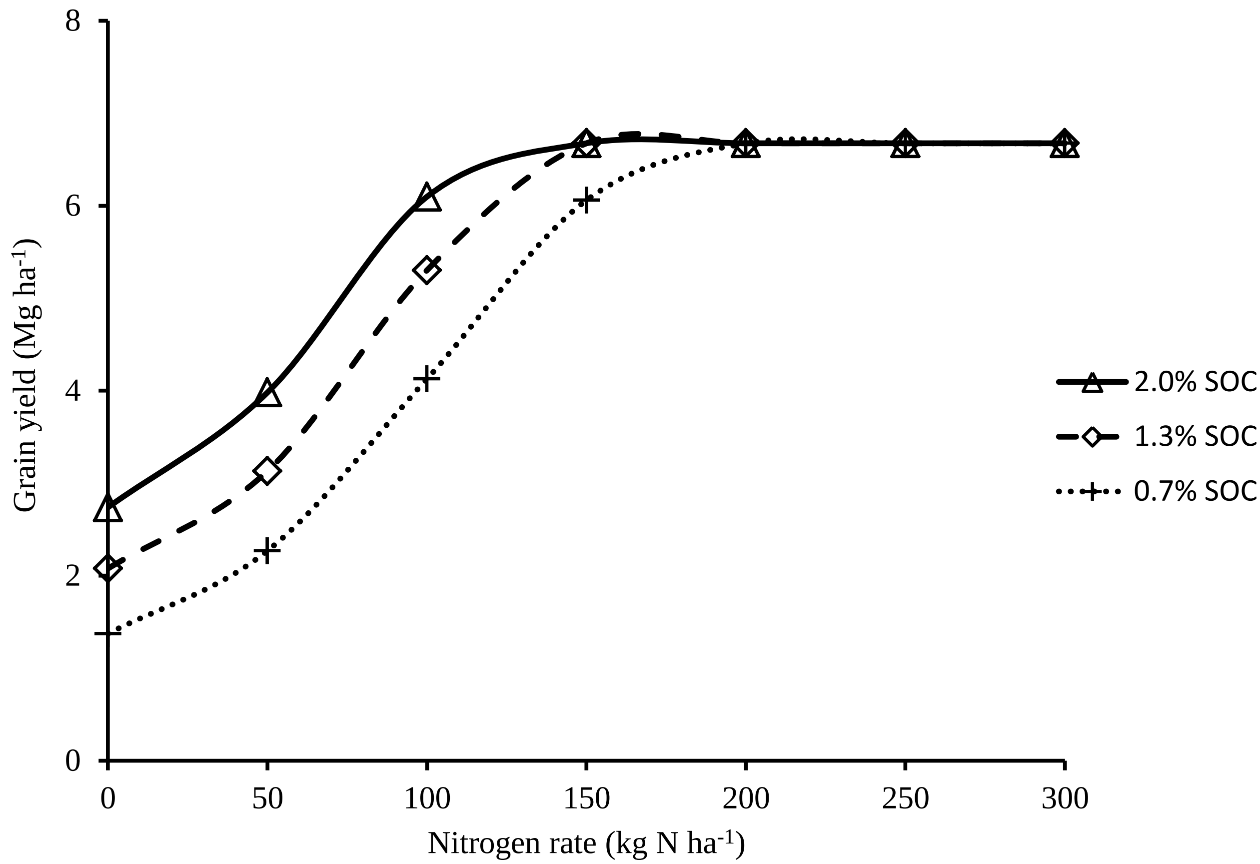


Fig. 2. Effects of SOC levels (2.0, 1.5 and 0.7% SOC) between 0-300 kg N ha^{-1} on winter wheat grain yield at LTE-Askov in Denmark

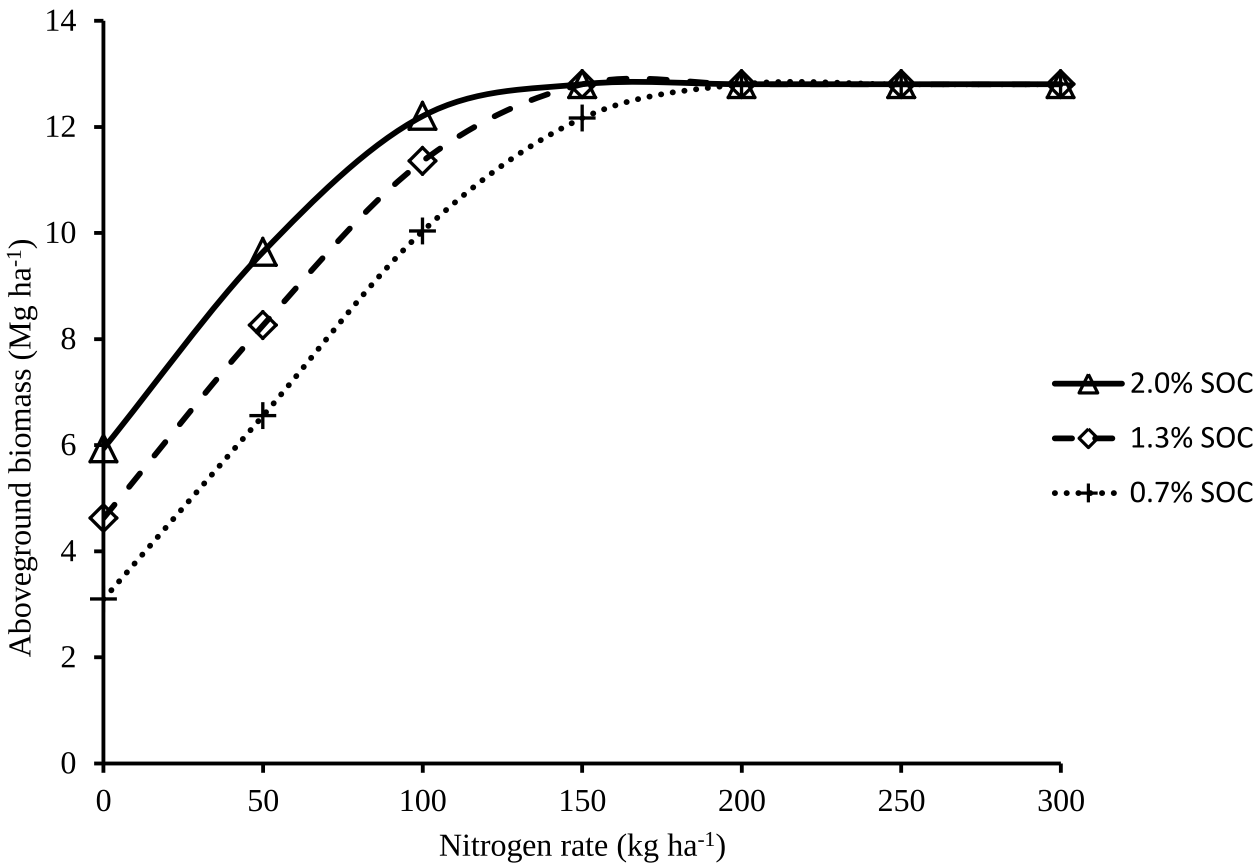


Fig. 3: Effects of SOC levels (2.0, 1.5 and 0.7% SOC) between 0-300 kg N ha^{-1} on winter wheat aboveground biomass at LTE-Askov in Denmark

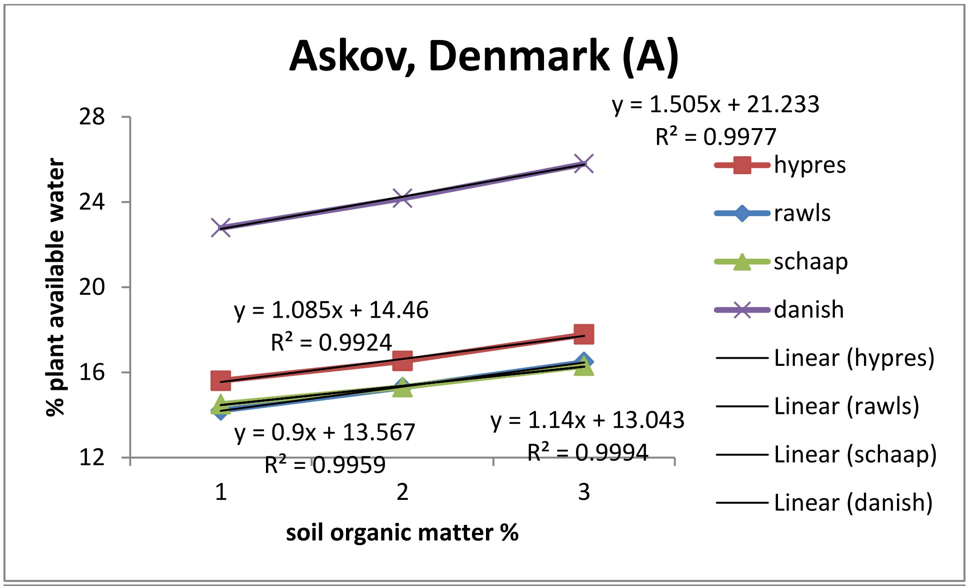
SOC effects on plant available water

The relationship between SOM and plant available water content were highly correlated with higher SOC retaining higher plant available water and vice versa in Askov and Padova soils (Fig. 4A and B). All 4 PTFs exhibited a significant correlation between SOM and plant available water with Danish PTF ((Borgesen and Schaap, 2005) showing the highest plant available water content in both Askov and Padova soils. Comparing the other three PTFs (schaap, Rawls and hypres), there was differences in plant available water content in Askov and Padova soils. In Askov soils, hypres PTF showed the second highest plant available water content followed by Rawls and Schaap PTFs whereas in Padova soils, Schaap PTF showed the second highest plant available water followed by Hypres and Rawls PTFs. However, when looking at the effect of increase in SOM the response in increase PAW is quite similar for the different PTFs and amounts to 1 % increase in PAW per percent increase in SOM.

SOC effects on root density

Irrespective of the SOC content, the winter wheat roots were found only up to 120 cm soil depth. Averaged across the soil profile, higher root density (cm cm^{-3}soil) was found in high SOC soil compared to low SOC soil (Fig.5). However, SOC effects on root density was recorded only up to

150 kg N ha^{-1}. The mean root density was 1.08, 0.87 and 0.62 cm cm^{-3} soil at high, reference and low SOC respectively. Differential effects of SOC was recorded along the soil profile with higher root density in high SOC soil in upper soil depth and the SOC effects diminished down the soil profile until no difference at 120 cm soil depth (Fig. 6). The mean root density was 2.6, 2.0 and 1.3 cm cm^{-3} soil at 15 cm soil depth and decreased to 1.4, 1.2 and 0.8 cm cm^{-3} soil in high, reference and low SOC respectively at 40 cm soil depth. The decreasing trend in root density was recorded across the SOC scenarios with increasing soil depth until no difference was recorded at 120 cm depth.



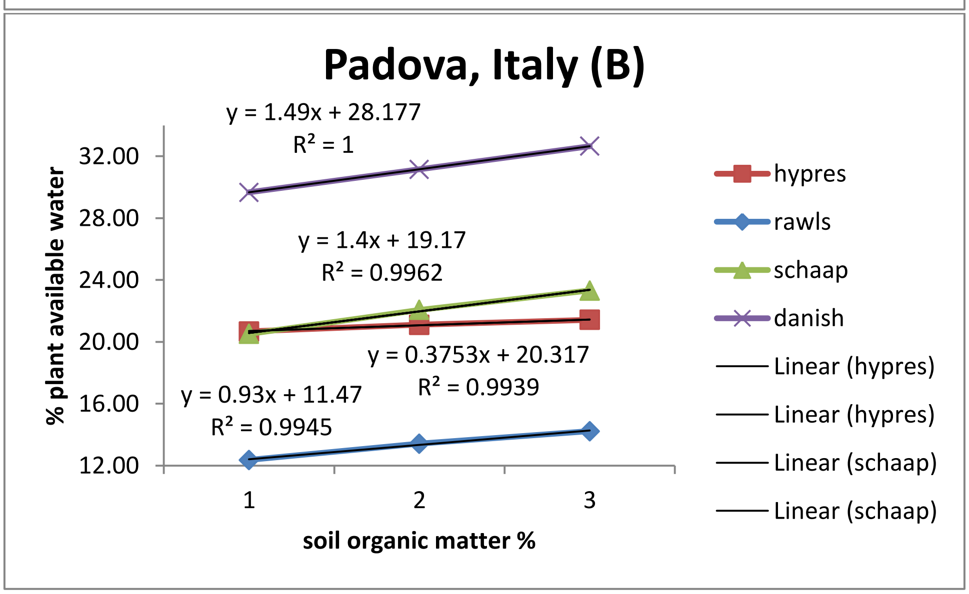


Fig. 4: Plant available water content (mm) at low, reference and high SOM contents in Askov (Denmark) and Padova (Italy) soils. .

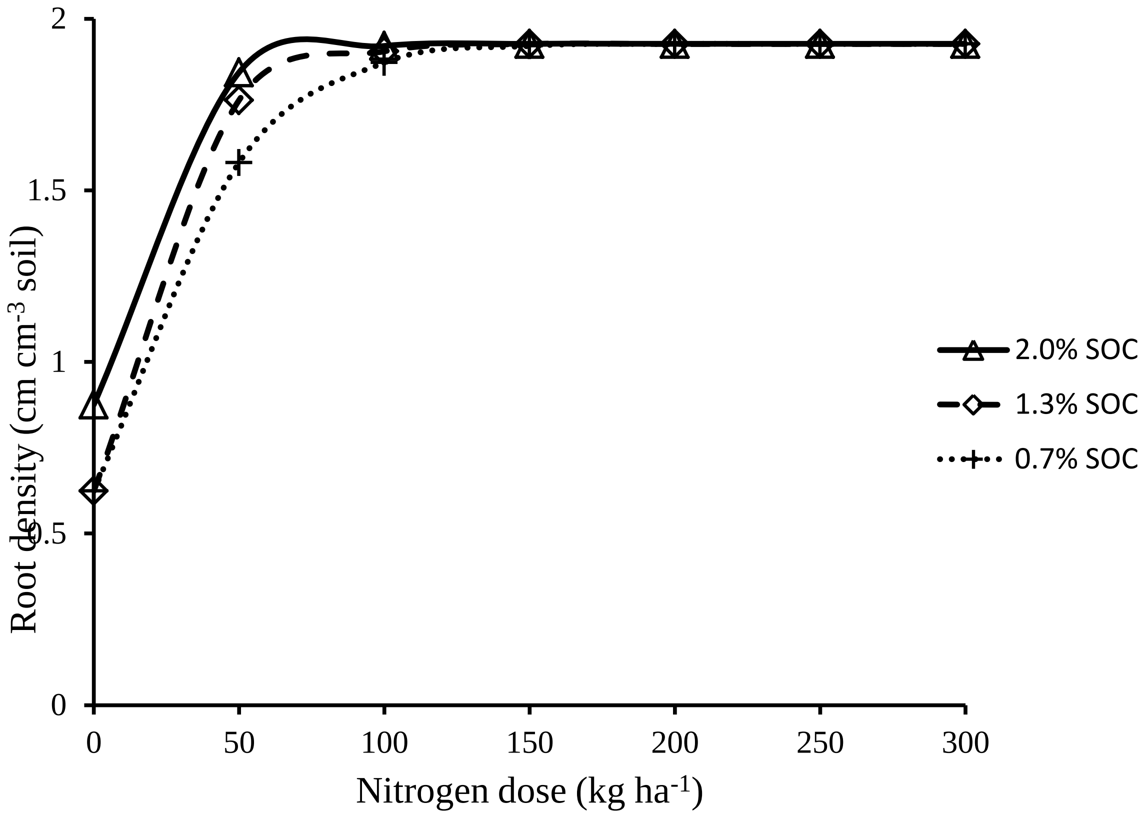


Fig. 5: Effects of SOC levels (2.0, 1.5 and 0.7% SOC) on root density with 0-300 kg N ha^{-1} rates at LTE- Askov in Denmark

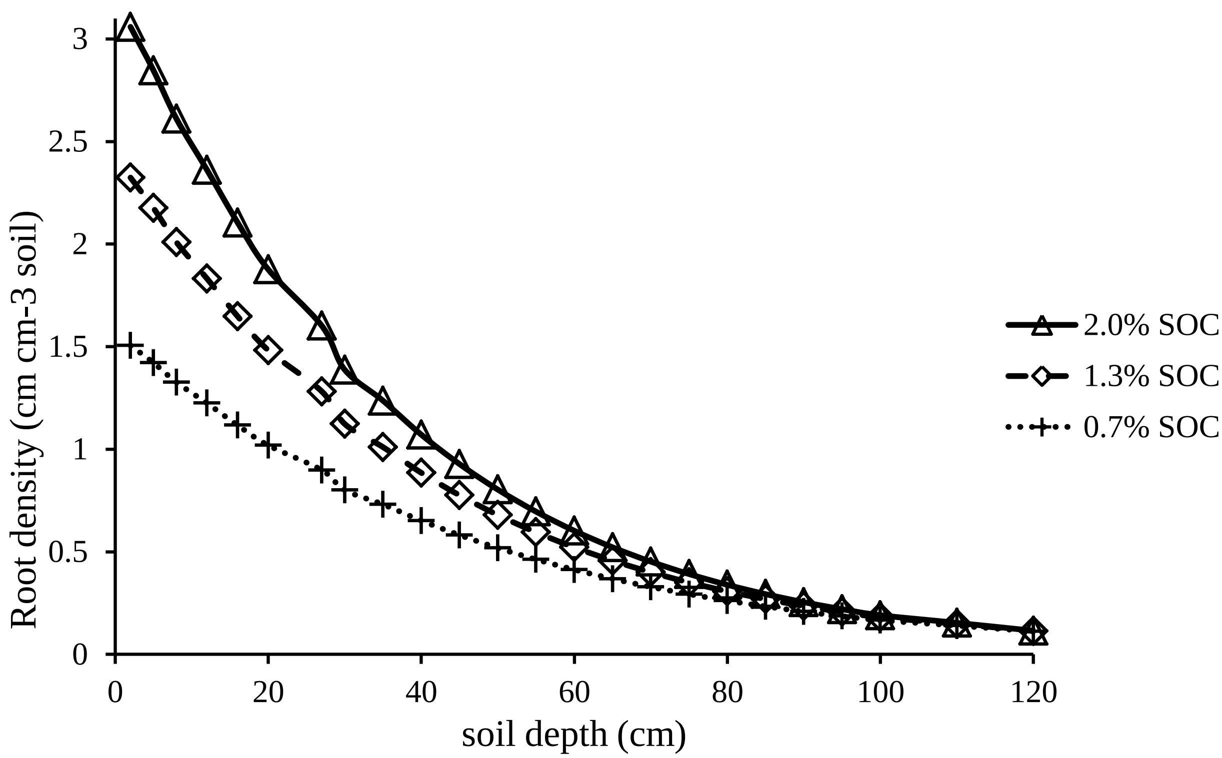


Fig. 6: Effects of SOC levels (2.0, 1.5 and 0.7% SOC) on root density at 0-120 cm soil depth at LTE-Askov in Denmark

Discussion

The global challenge to enhance 70% food and fodder production by 2050 with lower dependence on fossil-based inputs needs to be examined in the wider context of the nexus between agriculture, food security and climate change. The productive capacity of the land resources can be enhanced by protecting the functional capacity of soils, and SOC is the core soil fertility component providing nutrients, water and suitable plat-soil environment for crop productivity. Due to long term change dynamics of SOC, modelling approaches provide a good alternative to assess management effects by validating the simulation outputs with LTE data. SOC has multiple benefits in terms of enhancing the productive capacity of the soil due to its influence on soil physical, biological and chemical characteristics (Lal et al., 2007) and the significance can be gauged from the Kyoto Protocol Article 3.4, which states that SOC sequestration can contribute to reducing the GHG emission (European Commission, 2006). Management has significant effects on whether soil is a CO_2 sink or source and the magnitude of effects depend on the inherent soil characteristics and the context of location. Management can have a direct influence on SOM and thereof SOC, soil structure, nutrient and water holding capacity, infiltration rate, run-off and depletion of SOC can have adverse effects affecting crop productivity in terms of grain yield, biomass production, root biomass production and soil water availability (Lal et al., 2007).
We validated the model with a treatment with continuous wheat culture without NPK inputs and crop residues removed from Padova in Italy and the similar trend of simulated and measured data (Fig. 1) point lends credibility and robustness of the simulation exercise. The daisy model has previously been evaluated for simulation of crop grain yield, aboveground biomass accumulation, nitrate leaching, crop N uptake etc. in several model comparison exercise (DEWILLIGEN, 1991,Vereecken et al., 1991,Diekkrüger et al., 1995) including validation of crop yield, soil nitrogen, nitrogen accumulation in winter wheat in three sites in Netherlands (Hansen et al., 1991). In a comparison of 9 SOM models for management effects of land use, fertiliser, manure and rotation treatments in diverse climatic gradients from seven LTEs, Daisy performed well with similar margin of errors among other models (DNDC, RothC, CENTURY, CANDY, NCSOIL) and better than SOMM, ITE and Verberne models (Smith et al., 1997b).Due to the robustness of the Daisy model to be applied with minimum data in general arable production systems, the model has a distinct advantage compared to SOMM, ITE and Verbane, which are limited to the specific production systems.

SOC levels have effects on grain yield and aboveground biomass

Our study found a positive relationship between the SOC and winter wheat grain yields. Similar relationships were reported in several studies (Mikanova et al., 2012,Persson et al., 2008,Seremesic et al., 2011,Thomsen and Christensen, 2004,Yang et al., 2011). In our simulations, winter wheat grain and straw yields increased with increase in SOC, in consonance with another field experiment at LTE-Askov, where one-six years old ley phase (1996-2001) (Christensen et al., 2009) was tested to assess SOC and its effects on subsequent spring barley yields (2001-2004). Although, there was no significant SOC increase ($p<0.05$) in 0-20 cm soil, the mean SOC increase was 1100 kg C ha^{-1}(Christensen et al., 2009). Spring barley grain and straw yields and SOC increased with increasing ley age indicating the relationship between the yield and SOC. However, application of more than 90 kg N ha^{-1} nullified the ley effects on grain and straw yield, suggesting that the key fertility driver of the ley phase was provision of N. The insignificant SOC increase at $p<0.05$ between ley age can be attributed to short experimentation phase (1996-2004) due to long term turnover dynamics of SOC. The benefits of grass ley on spring wheat grain yields was reported from a 24 years trial at Jyndevad in Denmark, where N substitution rate of 15-27 kg N ha^{-1} was attained with long term catch crops use compared to no catch crop use without a yield penalty (Hansen et al., 2000).

SOC effects on root density, soil water and retention curve

The positive relationship between SOC and soil water content/retention curve has been reported in other studies (EMERSON, 1995,Rawls et al., 2003) including a study on 41 Danish soils (Resurreccion et al., 2011). A study in North Dakota in sandy, medium and fine textured soil demonstrated that soils with higher SOC retained more soil water irrespective of the soil types (BAUER and BLACK, 1992) supporting the hypothesis that SOC has a role in soil water retention. The Mualem-van Genuchten Model (Schaap and van Genuchten, 2006) is used for prediction of soil water content and hydraulic conductivity in which SOC is used as a factor. Different parameters for the Van-Genutchen model are based on Hypres, a European-wide soil database. Hence, our simulations of soil water content and moisture retention curve are optimized for European soils, which provides robustness in our findings.

Supporting our findings, the relationship between SOC and root density was found in shortgrass steppe soil profile with higher root biomass in the upper soil layers due to higher SOC content in (Gill et al., 1999). Higher SOC in the upper soil layer is attributed to the high decomposition rates in the 5-10 cm layer compared to soil layer below. Root density was also found to correlate with total SC and total SN in a maize field in New Zealand (Kusumo et al., 2010,Kusumo et al., 2011) indicating that the availability of C and N is conducive for more root growth.

Conclusion

Higher yields are attributed to enhanced availability of soil water and thereof plant nutrients and higher root biomass for uptake of nutrients and water resulting in enhanced crop productivity. Yield benefits were observed irrespective of the different ways of enhancing SOC like tillage treatments, inclusion of catch crop balanced fertilization, crop residue incorporation and other conservation practices. The evidence suggests that SOC can have significant effects on crop productivity at low N supply levels, which suggests that building SOC might allow less N fertilizer to be used to achieve the same yield.

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