# Quantifying the effect of soil organic carbon on wheat yield: a simulation study

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**Abstract**
Soil organic carbon (SOC) is an important component of the natural capital of soil. Increased SOC can benefit crop growth by influencing soil processes and functions such as mineral nitrogen (N) supply to crops through its effect on N cycling, and water supply to crops through its effect on soil water characteristics. However, the relative contribution of these soil processes to grain yield is poorly understood. Crop models are increasingly used to investigate farming system productivity. Using the Agricultural Production Systems sIMulator (APSIM) model, we investigated the effect of particular soil processes, as affected by increased SOC in the top 0.1 m of the soil, on grain production for three Australian farming sites. At each site, we simulated wheat yield in scenarios where increased SOC was manipulated in the model to affect: (1) N cycling (i.e. N supply); (2) soil water characteristics (i.e. water supply); or (3) the combined effect of N cycling and soil water characteristics. Scenarios were simulated across five N fertiliser rates. We found that at low fertiliser rates, the effect of increased SOC on N cycling significantly increased simulated wheat yields. There was no similar effect at high fertiliser rates. The effect of increased SOC on soil water characteristics was much smaller than that on N cycling, but higher SOC increased crop yield at two of the three sites at high fertiliser rates. Quantitative estimates of the effect of increased SOC on crop yield are important in the context of managing SOC in Australian grains farms.

**Key words**
Modelling, wheat, productivity, soil organic carbon, nitrogen, APSIM

**Introduction**
Soil organic carbon (SOC) is an important component of the manageable natural capital of soils (Dominati et al. 2010) and can deliver a number of important ecosystem services, including contributing to crop productivity through its effect on physical, chemical, and biological soil properties and functions. For example, soil organic matter is a major store and source of nutrients, especially nitrogen (N). Furthermore, increased SOC can increase soil water supply through its effect on soil water characteristics. Given the decrease of SOC in some Australian agricultural soils due to past management practices, there is potential for agricultural management to increase SOC (Lou et al. 2014), particularly in the top 0.1 m of the soil where the majority of changes to SOC occur (Davy and Koen 2011). Higher levels of SOC have been linked to increased agricultural crop productivity in wheat farming systems (Lal 2004). Some studies have investigated the mechanism of this relationship in Australian cropping systems (e.g. Whitbread et al. 2000). A limitation of such studies is that they neither investigate which of the soil properties affected by SOC have the greatest effect on yield, nor how the effects vary across a range of soil types and climatic regimes.

Agricultural cropping models are increasingly being used to investigate soil, climate, and productivity dynamics of agricultural systems. These models provide a method to quantitatively assess the contribution of particular soil properties and functions, as affected by SOC, to crop yield across a range of soil, climate and management combinations. The Agricultural Production Systems sIMulator (APSIM) model has been developed in Australia and extensively validated for Australian wheat cropping systems, making it ideal for use in this study (Holzworth et al. 2014). APSIM has the inbuilt capacity to dynamically simulate changes in SOC and the resultant effect on N cycling which in turn influences N supply to crops. Carbon inputs to soils affect carbon flows between the carbon pools in APSIM which in turn affects the corresponding N flows which are calculated using the C:N ratio of the receiving N pool. This functionality is central to the SoilN module in APSIM (Holzworth et al. 2014). APSIM does not currently have the inbuilt capacity to dynamically simulate the effect of SOC on soil water characteristics which influence water supply to crops. However, the effects of SOC on soil water characteristics can be simulated by user-intervention (i.e. the user specifies parameter values that reflect changed SOC).

We report a simulation study on the effect of N cycling and soil water characteristics, as affected by changes in SOC, on grain yield in three Australian wheat farming systems using the APSIM model. We quantified the contribution of (1) N cycling (i.e. N supply), (2) soil water characteristics (i.e. water supply), and (3) the combined effect of N cycling and soil water characteristics to wheat yields.

**Methods**

The APSIM model (v7.5) was used to simulate soil, carbon, N, and water dynamics as well as grain production at three study sites. Study sites were chosen from within three different Australian wheat production agro-ecosystems; the Brigalow (26.88°S, 150.82°E) region in northeast Australia, the Mallee (35.80°S, 142.88°E) region in southeast Australia, and the Liebe region (30.27°S, 116.66°E) in Western Australia. Dryland cropping was practiced at all sites. Soil textures at the Brigalow, Mallee, and Liebe sites are clay, sandy clay loam, and sand, respectively. Soil parameter values used in APSIM were sourced from the APSoil database (www.apsim.info, accessed 5 May 2014), with the exception of more recently measured SOC content for the Mallee site (H van Rees 2014 pers. comm.). At each site, simulations were undertaken using the current SOC values in the soils (reflecting the past cropping system management) and with higher SOC values that reflect a theoretical SOC concentration that could be achieved under optimal management in the grain growing regions (Luo et al. 2014). To determine the relative effects of SOC on N and soil water supply to crops, four scenarios were simulated. In the first, termed the *Control* scenario, the soil with its 'original' SOC was simulated. In the second, the *Nitrogen Cycling* scenario, increased SOC affected only N cycling. In the third, the *Soil Water Characteristics* scenario, increased SOC affected only soil water characteristics. In the fourth, the *Combined Properties* scenario, SOC affected both N cycling and soil water characteristics. Pedo-transfer functions were used to relate the values of the main parameters affecting soil water in APSIM to SOC concentration (Palmer 2014).

Soil organic carbon in the top 0.1 m of the soil was increased from 1.19 to 2.19 % at the Brigalow site, from 1.20 to 2.20 % at the Mallee site and from 0.68 to 1.68 % at the Liebe site. This level of increase was based on estimated achievable increase under optimal management (Luo et al. 2014). Soil water parameters in APSIM include drained upper limit, lower limit, saturation water contents, and saturated hydraulic conductivity (specified for each soil layer). The water holding capacity of the soil, which is the total amount of water in the soil that a plant can access, is defined as the soil water held between the drained upper limit and the lower limit. These water parameters (drained upper limit, lower limit, saturation, saturated hydraulic conductivity) and bulk density were modified in the *Soil Water Characteristics* scenario. In this scenario, the plant available water in the top 0.1 m increased by between 1 and 3 mm with increased SOC, depending on the soil texture at the site. To avoid long-term changes of soil and water properties, which would confound the study, the SOC, mineral N, water, and surface residue values were 'reset' to initial values annually on the 1st January. Each scenario was simulated across five N fertiliser rates (0, 50, 100, 150, 200 kg N/ha). Management operations were specified to reflect common practice in each region with a continuous wheat cropping rotation and a summer fallow simulated at all sites. Daily climate data from 1963 to 2012 were obtained for each site from the meteorological stations nearest to the study sites. Using standard APSIM parameters the cultivars Hartog, Yitpi, and Mace were simulated at the Brigalow, Mallee, and Liebe sites respectively. Using the R statistical package (v3.1.2), the Wilcoxon signed-rank paired test was used to analyse the simulated yield for a significant difference between the *Control* scenario and the other scenarios.

**Results and discussion**

*Nitrogen Cycling scenarios*

Higher SOC significantly increased simulated wheat yields at low fertiliser rates at all three sites (Figure 1a, b, c). However, at higher fertiliser rates (between 100 and 200 kg N/ha depending on the site), high SOC had little or negligible effect on yields. In the Mallee site simulation with 0 kg N/ha, for example, the median yield in the *Nitrogen Cycling* scenario was 0.5 t/ha higher than the median yield in the *Control* scenario, whereas with 200 kg N/ha there was no difference (Figure 1b). The negligible effect of increased SOC on yields at higher fertiliser rates was expected, as N fertiliser dominated the N supply at high fertiliser rates. At low N fertiliser rates, the N supply to the crop was dominated by N derived from mineralisation of organic N. This result is consistent with field studies (e.g. Grace et al. 1995) that highlight N supply to crops from the 'consumption' of the SOC natural capital occurs as SOC stocks run down. In this study, simulated SOC content was annually reset. In a farming system, SOC would be depleted and the yield benefit would diminish unless inputs of organic material replaced the loss.

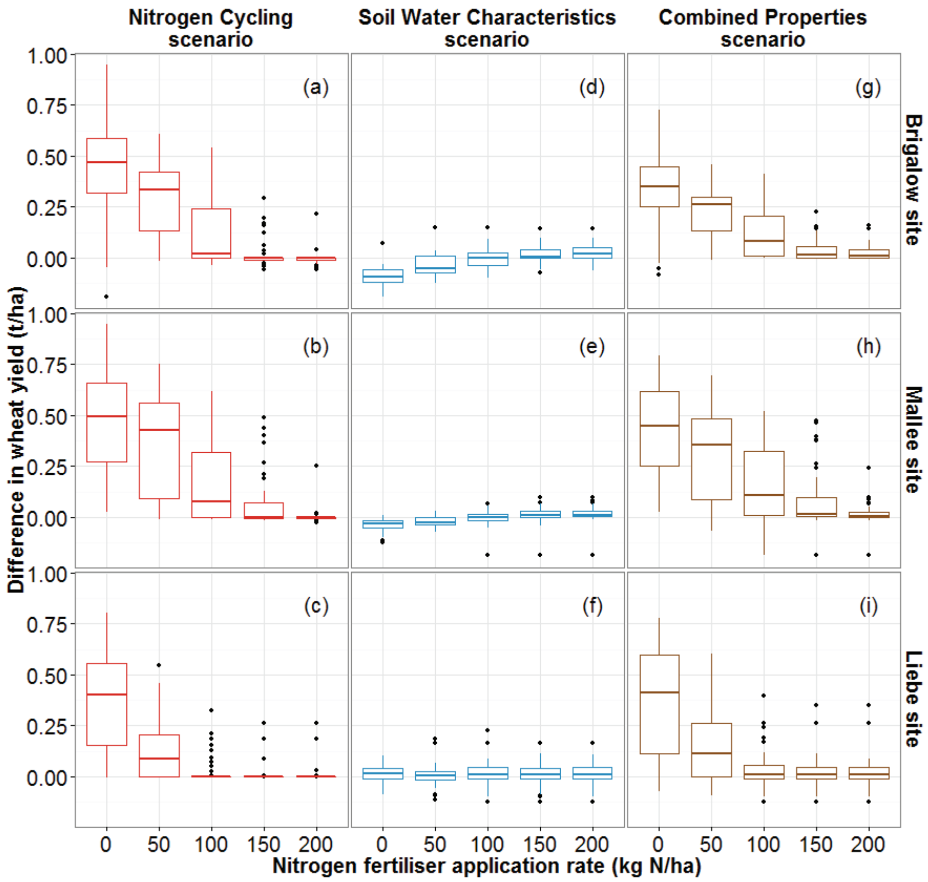


**Figure 1: The difference in the simulated wheat yield between the *Control* scenario and the *Nitrogen Cycling, Soil Water Characteristics*, and *Combined Properties* scenarios, given increased soil organic carbon, for the Liebe, Brigalow, and Mallee simulations, under five nitrogen fertiliser rates. The data displayed represents simulated wheat yield from 1963 to 2012. Boxes show the 25th and 75th percentiles and the line shows the median value. Whiskers extend to the 10th and 90th percentiles and outliers are shown as points.**

*Soil Water Characteristics scenarios*

The effect of changed soil water characteristics on simulated yields was much smaller than for the *Nitrogen Cycling* scenarios at all sites and there were interactions with fertiliser rate and site (Figure 1d, e, f). At low (i.e. 0 or 50 kg N/ha) fertiliser rates, the median yields in the *Soil Water Characteristics* scenarios were slightly lower than those in the *Control* scenarios at the Mallee (0.06 - 0.08 t/ha, Figure 1e) and Brigalow (0.03 - 0.04 t/ha, Figure 1d) sites. However, in a small number of individual years, yields were higher. At higher (i.e. 150 or 200 kg N/ha) fertiliser rates, median yields at these sites were slightly higher (up to 0.02 t/ha) with greater SOC. At the Liebe site (Figure 1f), increased SOC did not significantly affect yield at any fertiliser rate, with the exception of 0 kg N/ha where median yield was 0.02 t/ha higher than the *Control.*

*Combined Properties scenarios*

At fertiliser applications up to 100 kg N/ha, the simulated yields of the *Combined Properties* scenario (Figure 1g, h, i) were more like those of the *Nitrogen Cycling* scenario (Figure 1a, b, c) than those of the *Soil Water Characteristics* scenario (Figure 1d, e, f). At low (i.e. 0 or 50 kg N/ha) fertiliser rates, the *Combined Properties* scenario resulted in similar (Liebe, Figure 1i) or lower (Brigalow and Mallee, Figure 1g, h) simulated median yields compared with those for the *Nitrogen Cycling* scenario. At these low fertiliser rates at the Brigalow site, the range in predicted yields (i.e. the difference between the 25th and 75th percentiles) was less in the *Combined Properties* (Figure 1g) scenario than in the *Nitrogen Cycling* (Figure 1a) scenario. At all sites, when 100 kg N/ha was applied, median yield was higher in the *Combined Properties* scenario (Figure 1g, h, i) compared with the *Nitrogen Cycling* scenario (Figure 1a, b, c). The increase was highest (0.06 t/ha, Figure 1g) at the Brigalow site. At this fertiliser rate, the range in predicted yields (i.e. the difference between the 25th and 75th percentiles) for the *Combined Properties* scenario was smaller at the Brigalow site, similar at the Mallee site, and greater at the Liebe site, when compared to the *Nitrogen Cycling* scenario. At the highest fertiliser rates (i.e. 150 or 200 kg N/ha) the altered N cycling due to increased SOC had negligible effect on yield (Figure 1a, b, c). However, the combined effects of N cycling and water supply due to increased SOC (i.e. the *Combined Properties* scenario) gave increased median yields at the Brigalow (Figure 1g) and Mallee (Figure 1h). The magnitude of the increases was similar to those in the *Soil Water Characteristics* scenario (Figure 1d, e).

*Conclusion and future research*

Soil organic carbon is an important component of the natural capital of the soil, delivering a number of important ecosystem services including crop productivity. This study found that the effect of increased SOC on N cycling provided a considerable yield increase at low fertiliser rates, but had very little effect at high fertiliser rates. Conversely, the effect of SOC on soil water supply had a much smaller effect on simulated yield than N cycling, but at high fertiliser rates, the increased water supply provided by higher SOC gave a small yield increase at two of the three sites. These findings are important in the context of managing SOC in Australian agricultural grains farms as they estimate the relative contribution of N supply and/or water supply, as affected by increased SOC, to wheat yield.

This study found relatively consistent effects of SOC across sites; however, considering a wider range of soil/climate/management combinations would provide a more comprehensive understanding of the magnitude of these effects. This study considered only the effect of SOC on grain yield. As SOC can influence many other ecosystem services, such as greenhouse mitigation (through SOC sequestration and nitrous oxide emissions) and off-site nitrate loss, further research could consider taking a more holistic view of the effects of SOC on ecosystem services and their benefits to grain farming systems.

Currently APSIM simulates only the effect of SOC on N cycling, and not on soil water characteristics (without user-intervention). The difference between the yield variation and yield response produced by the *Nitrogen Cycling* and by the *Combined Properties* scenarios (Figure 1) indicates that APSIM may currently be overestimating the effect of increased SOC on wheat yield at low fertiliser rates. Conversely, APSIM may be underestimating the effect at high fertiliser rates. APSIM is a widely used simulation tool. While there is inherent uncertainty associated with estimating the productivity of farming systems, further insights into crop management might arise from simulations where SOC also affects soil water characteristics, particularly in situations of high SOC change. Future development of APSIM could consider making soil water characteristics dynamically responsive to SOC. This could enhance the accuracy of APSIM when simulating agricultural systems.

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