Grass-NEXT – A process-based model to explore nutrient and carbon dynamics in topographically complex grazed grasslands

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Keywords: Soil organic carbon; grazing systems; nutrient transfer; spatiotemporal model; sampling design

Abstract. Topographical features such as slope and aspect influence primary production, animal behavior and nutrient return to grazed grasslands. A new model was developed based on data collected during 40+ years of research in hill country landscapes, a long-term experiment on varying phosphorus (P) fertilizer rates and associated sheep stocking regimes. The Grass-NEXT model was able to simultaneously simulate total soil P (TSP), soil organic carbon (SOC) and total soil nitrogen (TSN) stock change and distribution in a topographically complex (hill country) landscape from 2003 to 2020. This model provided a basis for exploring, accounting, and reporting on changes in TSP, SOC and TSN stocks in response to current management practices (e.g., varying amounts of P fertilizer rates applied) in complex grazed systems. The model provided insights on both the combination of topographical features that provided the largest spatial and temporal variability across the landscape, and where more intensive sampling is required to detect a significant minimum change of 3% in total SOC stocks. Further work could improve the quantification of grazing activities and excreta deposition that would help to detect specific clusters of variation on topographical complex landscapes to facilitate soil sampling design.

Introduction

New Zealand hill country landscapes (slopes >15º) account for more than 50% of the country's permanent grasslands (around 4.1 million ha) and are the base for the sheep and beef pastoral industry (Kemp and López 2016). Understanding the nutrient and SOC spatial patterns across hill country landscapes is a key element in the design of any SOC stock monitoring regime and to estimate the spatial and temporal effects of topography and animal behavior on soil C changes. The Grassland Nutrient EXplorer and Transfer model (Grass-NEXT) can simultaneously simulate total TSP, SOC and TSN stock change and distribution in a topographically complex landscape (hill country). The model provides (i) a tool for exploring the influence of management practices including P fertilizer regimes and grazing practices, which are considered major drivers of the C cycle in grasslands soils (Poeplau et al. 2018) and (ii) a portable basis for designing soil sampling strategies and quantifying SOC stocks in topographically challenged hill land. Specifically, this model could be useful to estimate the expected SOC stock changes and its standard variation within topographical features (slope and aspect), which are essential for the calculation of minimum detectable differences (MDD) recommended to determine the number of samples needed (or alternatively the number of years required) to detect a statistically SOC change for a given number of samples (Smith, 2004). As a showcase of the Grass-NEXT model functionalities, the objectives of this study were to i) simulate the spatial distribution and temporal changes of P, SOC and N simultaneously in hill country as influenced by topography (slopes and aspects) over time and ii) explore the role of Grass-NEXT as a process-based model, to assist the soil sampling design and monitoring of SOC stocks in topographically complex landscapes.

Methods

Field location and topography

Ballantrae Hill Country Research Station is in southern Hawke's Bay (408180S 1758500E). The farmlet used in this study forms part of a larger study described in Lambert et al. (2000). Since 1980 the 8.1 ha low fertility (LF) farmlet has received 125 kg single superphosphate (SSP) ha^{-1} yr^{-1} and stocked with sheep at 10.6 SU ha^{-1} (1 SU = 550 kg dry matter (DM) intake). For a more comprehensive description of the LF farmlet and livestock carried, see Mackay et al. (2021a). Soil samples were collected from permanently marked sites on three slope [Low (LS; 0°–12°), Medium (MS; 13°–25°) and High slope (HS;>25°)] and three aspect categories relative to the true north as [East (E; 35–155°), Northwest (NW; 155°–275°) and Southwest aspect (SW; 275°–35°)] to a depth of 300 mm in 2003 and in 2020. A more detailed description of soil sampling procedures and soil sample analyses can be found in Mackay et al. (2021a, b).

Accounting for the heterogeneity of carbon dynamics in topographical complex landscapes through the Grassland Nutrient EXplorer and Transfer (Grass-NEXT) model

The locally calibrated Grass-NEXT model (Bilotto et al. 2022) was developed using the simulation and modelling tool Insight Maker (Fortmann-Roe 2014). A wide range of soil attributes are accounted for, along with the influence of topography on primary production, pasture composition and animal behavior (including grazing, camping, and nutrient return), as well as how these affect the dynamics of the biogeochemical cycles of P, C and N soil stocks over time (Bilotto et al. 2022). To account for the effect of spatial variability on nutrient excreta return from livestock, equations that relate to slope classes were generated and adapted to aspects based on Saggar et al. (2015). The initial conditions for SOC stocks and bulk density were assumed from Mackay et al. (2021b) extended to a 300 mm depth. For simplicity, the Grass-NEXT model was used to simulate the spatial distribution and temporal changes of TSP, SOC, and TSN stocks in the LF farmlet between 2003 and 2020. Model parameters and equations used to calculate changes in TSP, SOC and TSN stocks to a depth of 300 mm are detailed in Bilotto et al. (2022).

Role of the Grass-NEXT model to assist the soil sampling design and monitoring of SOC stocks in topographically complex landscapes

The sampling strategy has a large influence on the sampling variance and can be evaluated ex ante. In this sense, this study requires a process of identification of potential sources of error and bias in SOC stock estimation with consistent methodologies to obtain the MDD and the number of samples required to obtain it (IPCC, 2006). Here, we assumed a topographically stratified static synchronous SOC stocks monitoring design (Mudge et al. 2020) where the same sites are revisited in each monitoring round, since this requires the smallest number of samples to detect a specified change in SOC stocks. For this study, we assumed 5 Mg ha^{-1} to a paired sample, two tail, t-test power analysis with a significance level of 0.05 and a power of 0.8. The modelled SOC stock changes and its standard variation (temporal variability) between 2003 and 2020 from the LF farmlet in Grass-NEXT model was essential to determine the number of samples required applying the MDD calculations (or alternatively the number of years required to detect a statistically SOC change for a given number of samples) (Smith, 2004).

Results and Discussion

Soil organic carbon and nutrients trends in topographically complex landscapes

The Grass-NEXT model was able to simultaneously simulate TSP, SOC and TSN stock change and distribution in a topographically complex (hill country) landscape from 2003 to 2020 (Fig. 1). The positive TSP balance, contrasted with the decline in the SOC and TSN stocks. While mean modelled annual changes in TSP stocks were greater on the LS than the other two slopes, no clear pattern was observed for annual SOC changes (Fig. 2). In agreement with previous findings (Schipper et al. 2011; Condron et al. 2012), there was no evidence to support that P fertilizer loading in grazing system increases SOC stocks. Often, a higher soil fertility is associated with a greater stocking rate (Schipper et al. 2011) and a faster rate of soil organic matter (SOM) decomposition caused by better herbage quality and higher earthworm activity (Condron et al. 2012). Based on international studies conducted on long-term temperate grazing systems, a linear increase of SOC and TSN stocks would be expected in soils with low SOM levels or after crop rotations (Coonan et al. 2019). However, when soils are near C saturation, large amounts of C and N inputs in long-term pastures could be counterbalanced by an exacerbation of their losses or a significant reduction of inputs (Schipper et al. 2011), maintaining or slightly declining SOC (Di et al. 2018) and TSN stocks (Bowatte et al. 2006). Despite the cycling of macronutrients such as P, C, and N in grazing systems coupled through biologically mediated soil and plant processes involved in SOM turnover, as TSP is progressively increased, SOC and TSN concentrations ruled by isometric stoichiometry appear to be progressively decoupled from TSP concentrations (Cleveland and Liptzin 2007)

Insights from spatial and temporally modelling of SOC stocks in topographically complex landscapes

The modelled results are of key relevance for planning soil sampling strategies to measure changes in SOC stocks in future experiments in topographically complex landscapes. Although the largest spatial and temporal variability was simulated at LS and SW aspects, LS and MS from NW and E aspects would require a more intensive sampling regime (>100 samples, Fig. 2) given the lower changes in SOC stocks. Similarly, Mackay et al. (2021a) found the highest spatial variation in LS from NW aspects. Long-term pastures facing NW and E aspects would require a longer period to detect a significant minimum change of 3% in total SOC stocks. Smith (2004) found that an increase in net primary production (leading to increases in C inputs through litter and roots) might reveal significant changes in soil C after about 7-15 years. Long-term fertilizer regimes (125 kg SSP ha^{-1} $year^{-1}$) increase pasture production relative to non-fertilized regimes but a higher annual pasture production with the same grazing regime (grazing pressure) generates similar levels of C inputs (Bilotto et al. 2022). Moreover, the combination of soil covered by long-term pastures near C saturation (low changes of SOC stocks expected), the net transfer of nutrients in excreta from the grazing animal and the intricate micro-topographies of Ballantrae's landscapes (high spatial variability) make it difficult to detect SOC changes in periods shorter than 5 years. Emerging technologies including GPS monitoring and remote sensing techniques could improve the quantification of grazing activities and excreta deposition (e.g., Plaza et al. 2022).

Figure 1. Modelled annual mean phosphorus (P) in green, carbon (C) in red and nitrogen (N) in purple dynamics (pools and flows) and changes in soil P, C and N in LF farmlet from Bilotto et al. (2022). LF: 125 kg SSP ha^{-1} $year^{-1}$ since 1980. The parameters and symbols are listed and explained in Bilotto et al. (2022).

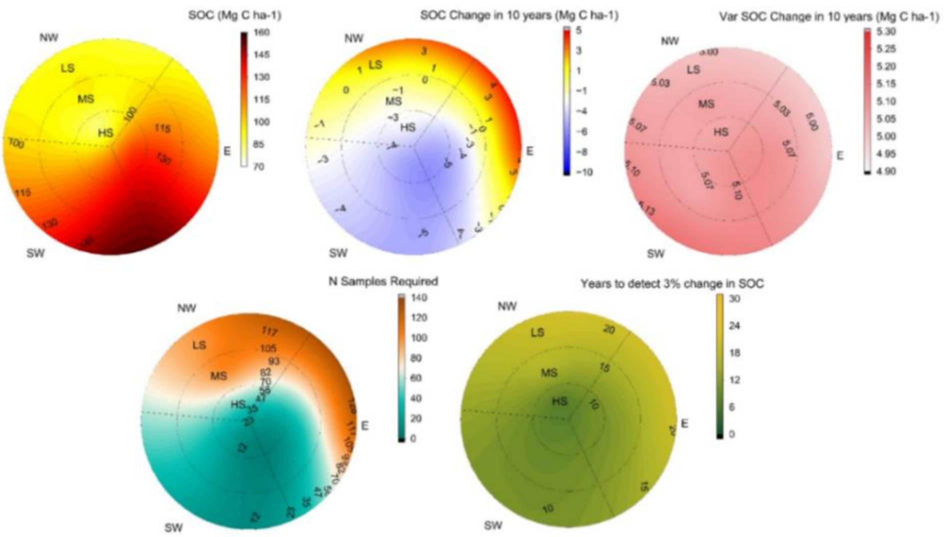

Figure 2. Modelled SOC changes in a period of 10 years, standard deviation, number of samples required and years to detect a 3% change in SOC stocks from 2003 in the LF farmlet (125 kg SSP ha^{-1} $year^{-1}$ since 1980) as affected by slope [Low (LS; 0°–12°), Medium (MS; 13°–25°) and High slope (HS;>25°)] and aspect position to the true north [East (E; 35–155°), Northwest (NW; 155°–275°) and Southwest aspect (SW; 275°–35°)].

Conclusions and/or Implications

The process-based Grass-NEXT model provides a basis for accounting, monitoring, and reporting on changes in TSP, SOC and TSN stocks in response to current management practices in complex grazed systems. Here, we demonstrate how Grass-NEXT could assist the soil sampling design and monitoring of SOC stocks in topographically complex landscapes. Pragmatic studies are needed to reduce the number of samples required and identify representative sites in long-term grazing systems to minimize the cost of on-farm SOC stock monitoring and auditing systems.

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