The potential supply of carbon-related ecosystem services from land management choices in Alberta's agricultural lands

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Abstract

Despite the growth of market-based approaches to maintain carbon-related ecosystem services (ES) in agricultural lands, practical methods that account for shifting historical baseline and additionality under local environmental and management conditions remain unresolved. To address this data gap for Alberta's agricultural lands, we developed spatially explicit organic carbon models for three dominant land-use types of rangeland, pastureland and cropland in an agricultural watershed to estimate the supply of organic carbon stock in soil (SOC) and aboveground plant biomass production (AGB) from a range of land management scenarios. Here we provide a summary of the modeling methods and results, with a focus on the impacts of land management scenarios related to grazing management, pasture vegetation improvement, and land conversion over a 10- and a 30-year simulation period.

The results showed a pronounced variation in the historic supply of SOC and AGB in the studied watershed. Overall, the implementation of different land management scenarios resulted in a diverse range of gain or loss in SOC and AGB across the watershed. The magnitude of gain or loss in SOC and AGB from the implemented land management scenarios varied spatially depending on the land use type, land management history, length of the implementation period, and local variability in ecosystem responses to particular management practice. Therefore, cautious need to be considered in regards to proposing the examined land management scenarios as beneficial management practices across Alberta's agricultural lands.

The information and knowledge developed provide a foundation to understand better market opportunities associated with conservation and restoration of the carbon-related ES in agricultural lands of the province. Serving as a starting place, stakeholders can build on this information to explore various land management practices that potentially lead to long-term provision of carbon-related ES and resilient of socio-ecological systems in Alberta's agricultural lands. The information and knowledge developed through this project will be integrated into a decision support tool that includes a wider range of ES and land management scenarios to develop credible and transparent market programs for protecting and enhancing multiple ES in Alberta's agricultural landscapes.

Keywords: Carbon markets; ecosystem models; grazing management; land conversion, land use types; plant biomass production; soil carbon stock.

1. Introduction

Recently, much attention has been paid to utilizing a framework to guide the conservation and restoration of ES through innovative approaches of incentivizing conservation and restoration activities (Jellinek et al., 2019). Among these approaches, the land-use carbon market has received the most attention (Salzman et al., 2018). A clear example of carbon market activities is the allocation of carbon credits for land management practices that have the potential to protect or even enhance carbon storage in agricultural lands (Jack et al., 2008). Besides a documented conservation issue or restoration plan, robust, reliable and comparable data on the provision of ES necessarily underlie policies incorporating ES valuation into conservation and restoration planning process (Daily et al., 2009). However, for most of the geographic regions, we generally lack spatially explicit, comprehensive data on the provision of ES that are needed to inform policy. Despite the rapid growth of land-use carbon markets over the last 20 years, they often lack appropriate historical baseline and additionality assessments, making it difficult to evaluate the effectiveness of implemented management actions (Salzman et al., 2018). Particularly, more studies are needed to conclude a diversity of land management practices that may lead to tradeoffs between agricultural production and the provision of various ES in a specific geographic region (Power, 2010).

Carbon-related ES provided through organic carbon stock in soil, and aboveground plant biomass production, are critical services that ensure the provision of several other ES in agricultural lands (Adhikari and Hartemink, 2016; Hungate et al., 2017). Application of biogeochemical ecosystem models, such as the CENTURY Ecosystem Model, is among the best available means to account for the provision of carbon-related ES across the landscapes that are highly heterogeneous in space and time (e.g., Lugato et al., 2014; Campbell and Paustian, 2015; Dimassi et al., 2018; Sándor et al., 2018). Using the CENTURY Ecosystem Model, we developed spatially explicit organic carbon models for three dominant land-use types of rangeland, pastureland and cropland in a representative watershed to support better accounting of the impacts of a range of land management scenarios on the supply of organic carbon stock in soil (SOC) and aboveground plant biomass production (AGB) and their potential tradeoffs. Specifically, we use carbon offsets to explore how science can inform key design challenges in carbon-related ES markets, including metrics for measuring losses and gains as well as addressing issues related to historical baseline and additionality.

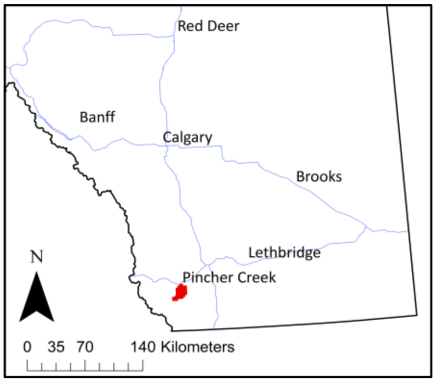
2. Methods

2.1. Study area

We conducted this study in the Indian Farm Creek (IFC) Watershed (141.45 km2), located in the southwest corner of Alberta (Fig. 1). The IFC Watershed lies in the productive Black Soil Zone of Foothills Fescue Natural Sub-region with annual precipitation of about 515 mm. The upper region of the watershed in the south characterized with short and complex slopes, the lower region in the north with much longer and simpler slopes and the dividing area between these two regions with very steep slopes Olson et al., 2011; Fig. 1). Agriculture is the primary land-use practice in the Watershed (97%) with crop and livestock production dominating the landscape. 39% of the Watershed is covered by annual crop (primarily barley) and 56% by perennial or permanent vegetation (primarily native ranges, pasture, and hay lands). Land use in the lower region of the Watershed is dominated by annual cropping, while the upper region has a greater proportion of native range, pasture, and hay land. Approximately a total of 32,000 head of cattle in cow-calf and feedlot operations, and 2500 grazing cattle were estimated to be in the Watershed (Olson et al., 2011).

2.2. Developing spatially explicit organic carbon models

We used the process-based plant-soil ecosystem model, CENTURY (v. 4.6; Parton et al., 1987; Parton et al., 1988; Parton et al., 1989) as biophysical plant biomass production and soil carbon model. The CENTURY model empirically derived equations and curves to simulate biophysical processes involved in carbon and nutrient dynamics at a monthly time step (Parton et al., 1988; Parton et al., 1989). The major input variables for the CENTURY model include monthly climate data, soil properties, atmospheric and soil nitrogen inputs, lignin content of plant material and land management information (Parton et al., 1989).



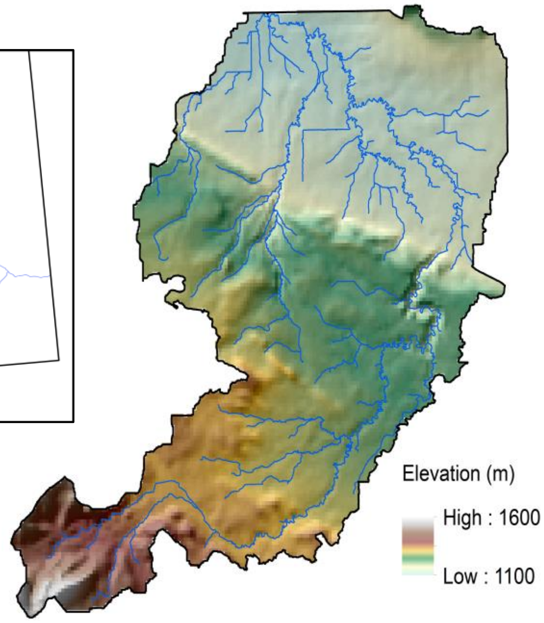


Fig. 1. Location of the IFC Watershed (red area) in the province of Alberta (left) together with the relief map of the Watershed (right).

We used spatial data on land use, soil, topography, and land management to delineate unique spatial modeling units for simulation of SOC and AGB in the IFC Watershed. 1011 soil-land use-topographic units were delineated that we considered as spatial modeling units for simulation of SOC and AGB in the Watershed (Fig. A2). We set up the CENTURY model for three dominant land-use types of rangeland, pastureland, and cropland by incorporating spatially-explicit information on historical grazing (season and intensity) and cropping practices (cultivation method, fertilizer application) collected from the Watershed. For rangeland and cropland models, we tested default vegetation parameter values, suggested vegetation parameter values for Alberta (based on consultations with CENTURY Core Group at Colorado State University), and the most representative sets of vegetation parameter values for the black soils of the Foothills Fescue Natural Region that were obtained through an extensive parameterization and calibration of the CENTURY model (see Iravani et al., 2019 for further details). For the cropland model, we only incorporated default model parameter values for barley as the dominant crop in the Watershed.

We evaluated model performance for two land-use types of rangeland and pastureland by comparing time-series of simulated AGB with remotely-sensed NDVI-based AGB proxies (2001-2010). We selected the model runs with the most desirable performance (Iravani et al., 2019) to simulate historic supply of SOC and AGB, as well as impacts from land management scenarios. Additional details on the development of carbon models are provided in Appendix 1.

2.3. Impacts of land management scenarios

We evaluated the potential supply of SOC and AGB from the land management scenarios related to grazing management, pasture vegetation improvement, and land conversion. We employed the organic carbon models built for rangeland and pastureland to simulate the potential supply of SOC and AGB from grazing management scenarios. We defined grazing scenarios as a combination of grazing season (or timing of grazing) and grazing intensity (or density of grazing) scenarios. In our simulation, the “historic grazing season” represented historical timing of grazing, and the “historic grazing intensity” represented the historical intensity of grazing implemented in the Watershed. We simulated historic supply of SOC and AGB under historic grazing season and grazing intensity. We then examined the impact of change in either of the grazing season and grazing intensity (e.g., under historic grazing season but a lower grazing intensity scenario, or under proposed grazing season scenarios but historic grazing intensity) or both (e.g., under proposed grazing seasons and a lower grazing intensity scenario).

In addition, we employed the organic carbon models built for the pastureland and cropland to simulate the impact of pasture vegetation improvement by perennial legume forage species, and conversion of cropland to perennial forage or permanent vegetation, respectively. We simulated historic supply of SOC and AGB under historical land use and management practices. We then examined the impact of these scenarios by comparing with the historic supply of SOC and AGB.

We evaluated the impacts of land management scenarios over a 10- (2001-2010) and a 30-year (1981-2010) simulation period. We determined impacts of individual land management scenarios as the absolute change in the supply of SOC and AGB relative to the historic supply of these ES at an annual time step, which was then averaged over the entire length of the simulation periods (10- and 30-year). Further details of simulated land management scenarios and examination of their impacts are provided in Appendix 2.

3. Results

3.1. Historic supply of SOC and AGB

The historic supply of SOC and AGB varied spatially and among different land-use types (Fig. A5). Across the Watershed, the SOC was estimated to be greater in rangelands compared to the pasturelands and croplands. It ranged from 50.8 to 90.4 ton/ha (on average 70.3 ton/ha) in rangelands, 37.3 to 89.5 ton/ha (on average 55.7 ton/ha) in pasturelands and 25.4 to 55.8 ton/ha (on average 40.9 ton/ha) in croplands. In contrast to SOC, AGB was estimated to be greater in pasturelands compared to rangelands, where it ranged from 1800 to 3700 kg/ha in pasturelands (on average 2750 kg/ha) and 1700 to 2650 kg/ha in rangelands (on average 2150 kg/ha) across the Watershed (Fig. A5).

3.2. Impacts from land management

3.2.1. Grazing management scenarios

Overall, the response of SOC and AGB to the proposed changes in grazing season and grazing intensity varied among grazing management scenarios and land use types. In addition, the range of change in SOC as a result of the implementation of the grazing scenarios revealed to be wider in the 30-year compared to the 10-year simulation period across spatial units associated with both rangelands (Fig. 2) and pasturelands (Fig. 4). However, this difference in the range of change between the 10- year and the 30-year simulation periods was less pronounced for AGB in both rangelands (Fig. 3) and pasturelands (Fig. 5) of the Watershed.

Across rangelands of the Watershed, the response of SOC to the changes in grazing season and grazing intensity varied spatially and among grazing management scenarios. Under historic grazing intensity, the short duration rotation grazing scenarios and the rest rotation grazing scenario compared to the historic grazing season resulted in a gain in SOC in the majority of spatial units, a pattern that was more apparent for the 30-year than for the 10-year simulation period. While, for both simulation periods, change from historic grazing season to summer rotational and deferred rotation grazing scenarios resulted in a loss in SOC in the majority of spatial units (Fig. 2). In contrast to the diverse direction and magnitude of changes observed from the implementation of grazing season scenarios, the 10% lower grazing intensity scenario resulted in a gain in SOC in the majority of spatial units under both historic grazing season and the implemented grazing season scenarios. However, this gain in SOC under a 10% lower grazing intensity scenario was more pronounced for summer rotational and deferred rotation grazing scenarios and under the 30-year than the 10-year simulation period (Fig. 2).

The response of rangeland AGB to the proposed changes in grazing season and grazing intensity also varied spatially and among grazing management scenarios (Fig. 3). However, the observed patterns of change in AGB were different from the patterns observed in SOC. Under historic grazing intensity, the short duration rest rotation and deferred rotation grazing in the 10-year and 30-year simulation period, respectively, resulted in a gain in AGB in the majority of spatial units. While, change from historic grazing season to the remaining grazing season scenarios resulted in a loss in AGB in the majority of spatial units, a pattern that was more noticeable in the 30-year than in the 10-year simulation period (Fig. 3). The 10% lower grazing intensity scenario resulted in gain in AGB in the majority of spatial units under historic grazing season and summer rotational, deferred rotation and rest rotation grazing scenarios and loss or gain in AGB under the remaining grazing season scenarios. However, these patterns of gain and loss in AGB under a 10% lower grazing intensity scenario was more pronounced in the 30-year than in the 10-year simulation period (Fig. 3).

Similar to rangelands, the response of pastureland SOC to the proposed changes in grazing season and grazing intensity varied spatially and among grazing management scenarios (Fig. 4). However, the patterns of change in pastureland SOC was different from the patterns observed in rangeland SOC (Fig. 2, Fig. 4). Under historic grazing intensity, the implemented grazing season scenarios (except summer rotational grazing scenario) compared to the historic grazing season resulted in a gain in SOC in the majority of spatial units. However, this gain in pastureland SOC, that was more pronounced in the 10-year than in the 30-year simulation period, was smaller compared to gain in rangeland SOC under the implemented grazing season scenarios (Fig. 4). Similar to rangelands, the 10% lower grazing intensity scenario resulted in a gain in SOC in the majority of spatial units under both historic grazing season and the implemented grazing season scenarios, a pattern that was consistent in two simulation periods (Fig. 4).

The response of pastureland AGB to the proposed changes in grazing season and grazing intensity also varied spatially and among grazing management scenarios (Fig. 5). However, the patterns of change in pastureland AGB was different from the patterns observed in rangeland AGB (Fig. 3, Fig. 5). Also, the observed patterns of change in pastureland AGB were different from the patterns observed in pastureland SOC (Fig. 4, Fig. 5). Under historic grazing intensity, implementation of different grazing season scenarios (except the short duration deferred rotation grazing) resulted in a gain in AGB in the majority of spatial units, a pattern that was consistent in two simulation periods. However, this gain in AGB under the implemented grazing season scenarios was greater in pasturelands than in rangelands (Fig. 5). In contrast to pastureland SOC and rangeland

SOC and AGB, the 10% lower grazing intensity scenario resulted in gain or loss in pastureland AGB under historic grazing season and the implemented grazing season scenarios, a pattern that was consistent in two simulation periods (Fig. 5).

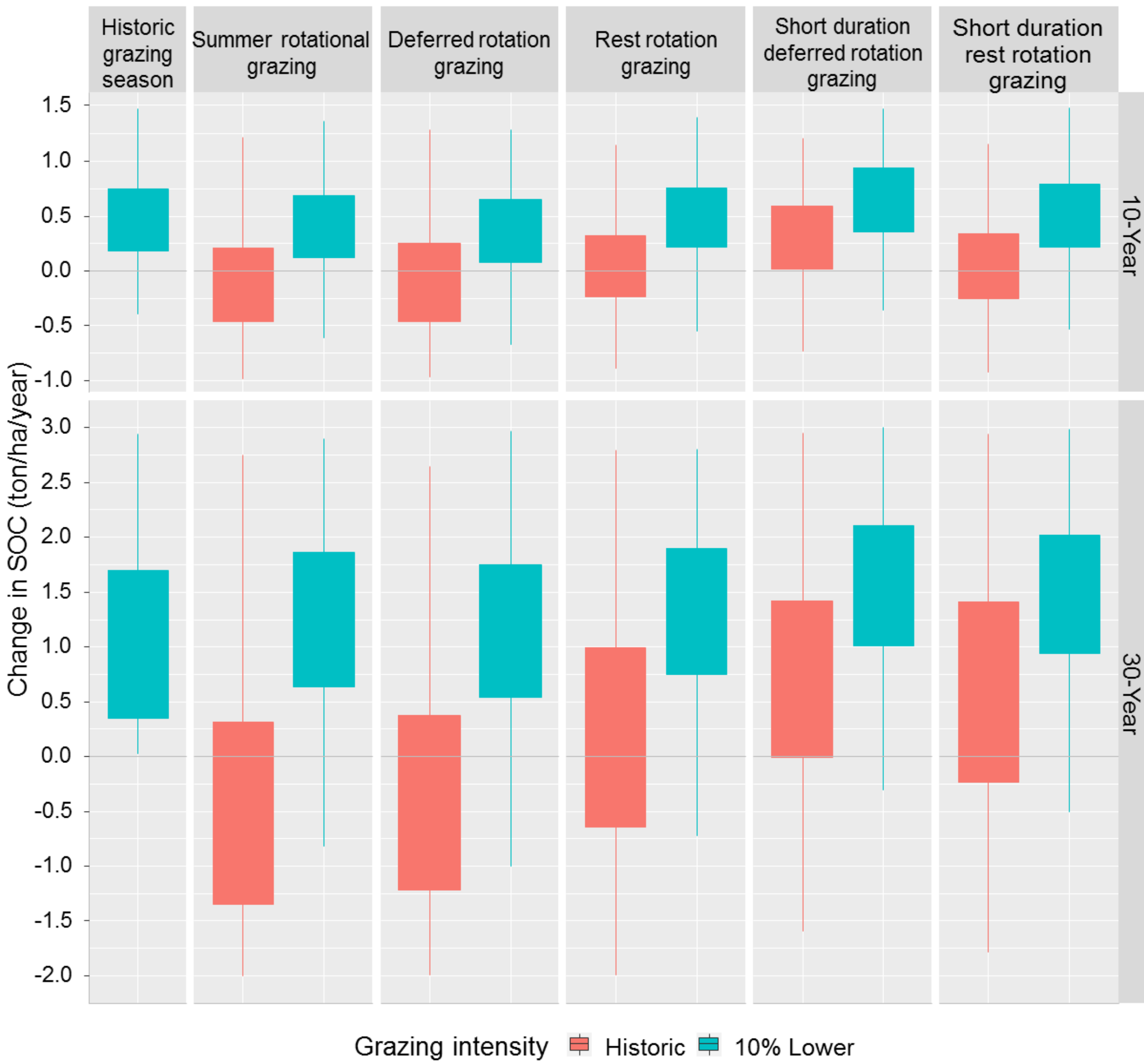


Fig. 2. Spatial variability in the response of rangeland SOC to implemented grazing season (vertical panels), and grazing intensity (boxplots with different colors) scenarios over 10-year (top row of panels) and 30-year (bottom row of panels) simulation periods. The most left panels show impacts of a 10% lower grazing scenario (low grazing) compared to historic grazing season and grazing intensity. The remaining panels illustrate impacts of the implemented grazing seasons compared to historic grazing season and grazing intensity (red boxplots) or joint impacts of the implemented grazing seasons and a 10% lower grazing intensity compare to historic grazing season and grazing intensity (red boxplots).

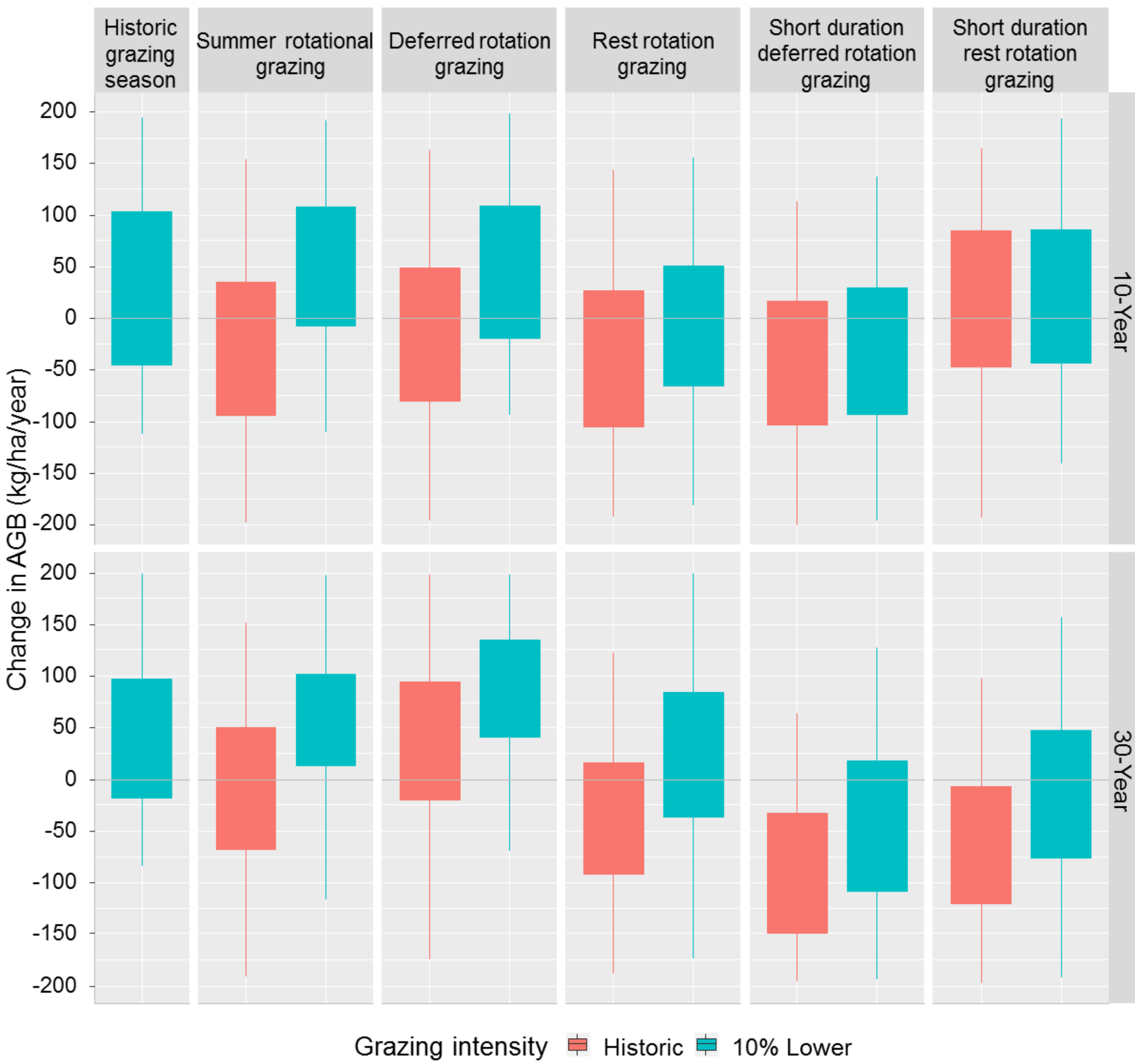


Fig. 3. Spatial variability in the response of rangeland AGB to implemented grazing season (vertical panels), and grazing intensity (boxplots with different colors) scenarios over 10-year (top row of panels) and 30-year (bottom row of panels) simulation periods. See Fig. 2 for further descriptions of the boxplots.

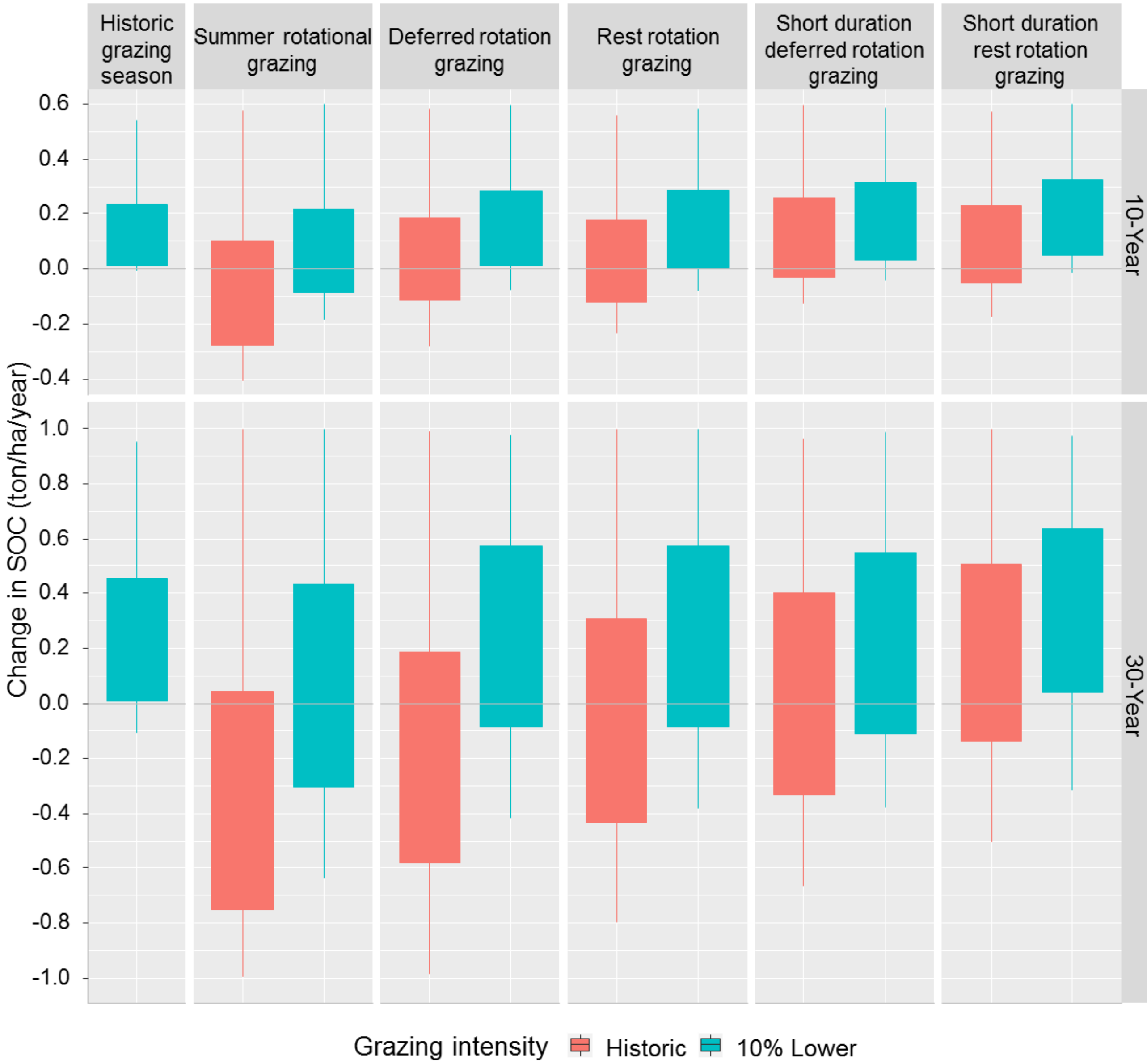


Fig. 4. Spatial variability in the response of pastureland SOC to implemented grazing season (vertical panels), and grazing intensity (boxplots with different colors) scenarios over 10-year (top row of panels) and 30-year (bottom row of panels) simulation periods. See Fig. 2 for further descriptions of the boxplots.

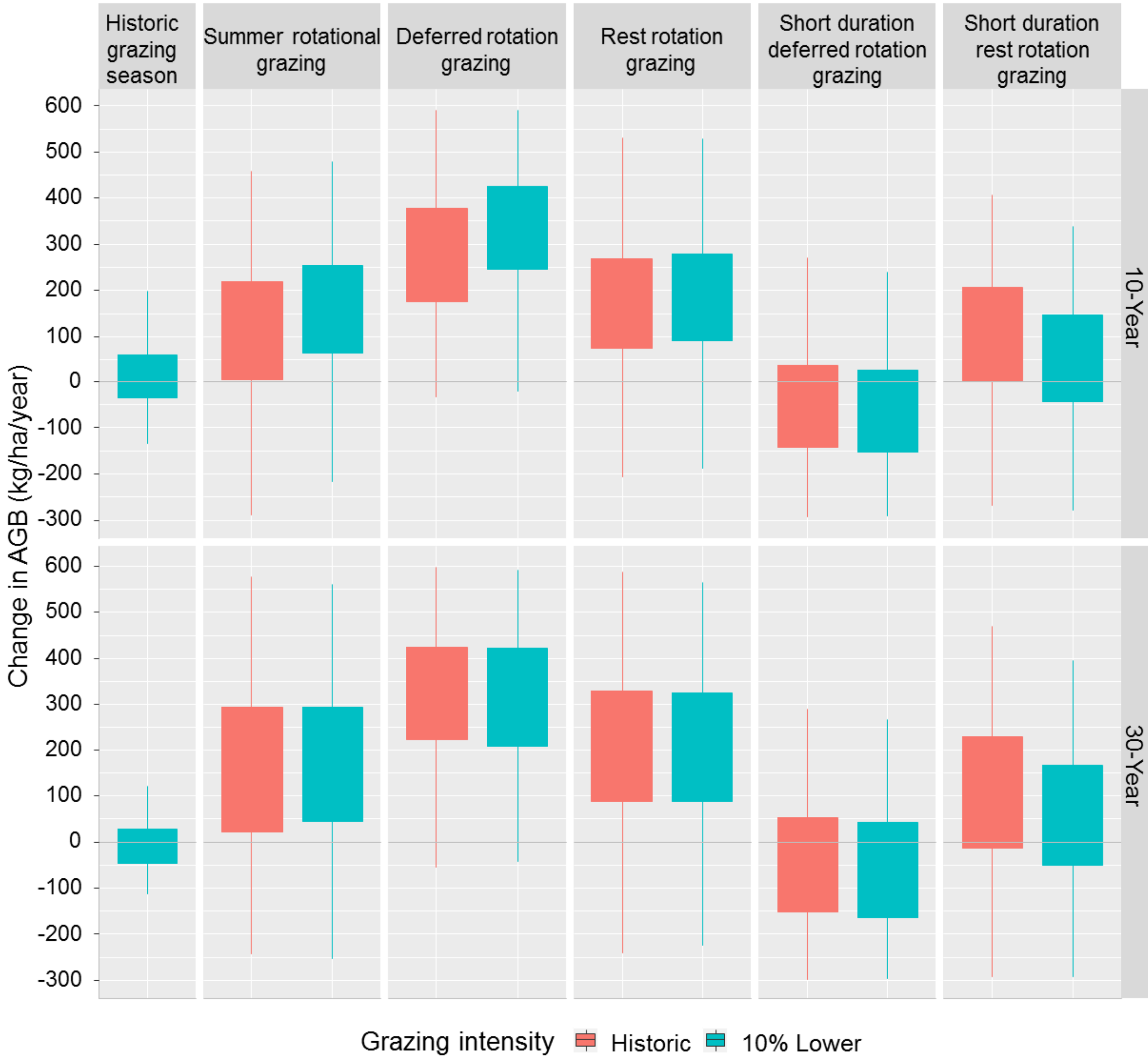


Fig. 5. Spatial variability in the response of pastureland AGB to implemented grazing season (vertical panels), and grazing intensity (boxplots with different colors) scenarios over 10-year (top row of panels) and 30-year (bottom row of panels) simulation periods. See Fig. 2 for further descriptions of the boxplots.

The no grazing scenario and short season grazing scenario were considered for conservation and sustainable use of natural areas. The response of rangeland SOC and AGB to these two grazing scenarios varied spatially and between two simulation periods (Fig. 6). Across rangelands of the watershed, exclosure from livestock grazing resulted in a gain in SOC but a loss in AGB, a pattern that was found to be stronger in the 30-year than in the 10-year simulation period (Fig. 6). The implementation of short season grazing under historic grazing intensity resulted in a loss in both SOC and AGB in two simulation periods. However, the implementation of short season grazing under a 20% lower grazing intensity scenario resulted in a gain in SOC and AGB in the 10-year simulation period and gain in SOC but gain or loss in AGB in the 30-year simulation period (Fig. 6).

Fig. 6. Spatial variability in the response of rangeland SOC (left) and AGB (right) to no grazing scenario (blue boxplots), as well as short season grazing scenario under historic (red boxplots) and a 20% lower grazing intensity scenario (green boxplots). The top and bottom row panels show simulation results for 10-year and 30-year periods, respectively.

3.2.2. Pasture vegetation improvement scenario

The low to high legume scenario was considered for pasture vegetation improvement by perennial legume species (alfalfa). The response of pastureland SOC and AGB to the vegetation improvement scenario of low to high legume varied spatially and between two simulation periods (Fig. 7). Across pasturelands of the Watershed, the implementation of low to high legume scenario resulted in a gain in both SOC and AGB. The magnitude of the observed gain in SOC was stronger in the 30-year than in the 10-year simulation period. While, gain in AGB was slightly greater in the 10-year than in the 30-year period (Fig. 7).

3.2.3. Land conversion scenarios

Two scenarios of cropland to perennial forage (alfalfa) and cropland to permanent vegetation were considered for the conversion of annual croplands to perennial vegetation. The response of cropland SOC to these two scenarios varied spatially and among the land conversion scenarios (Fig. 8). Across croplands of the Watershed, the implementation of both scenarios resulted in a gain in SOC. However, the magnitude of the observed gain in SOC was stronger under cropland to permanent vegetation scenario than under the cropland to perennial forage scenario. Also, the range of gain in SOC as a result of these scenarios revealed to be wider in the 30-year than in the 10-year simulation period (Fig. 8).

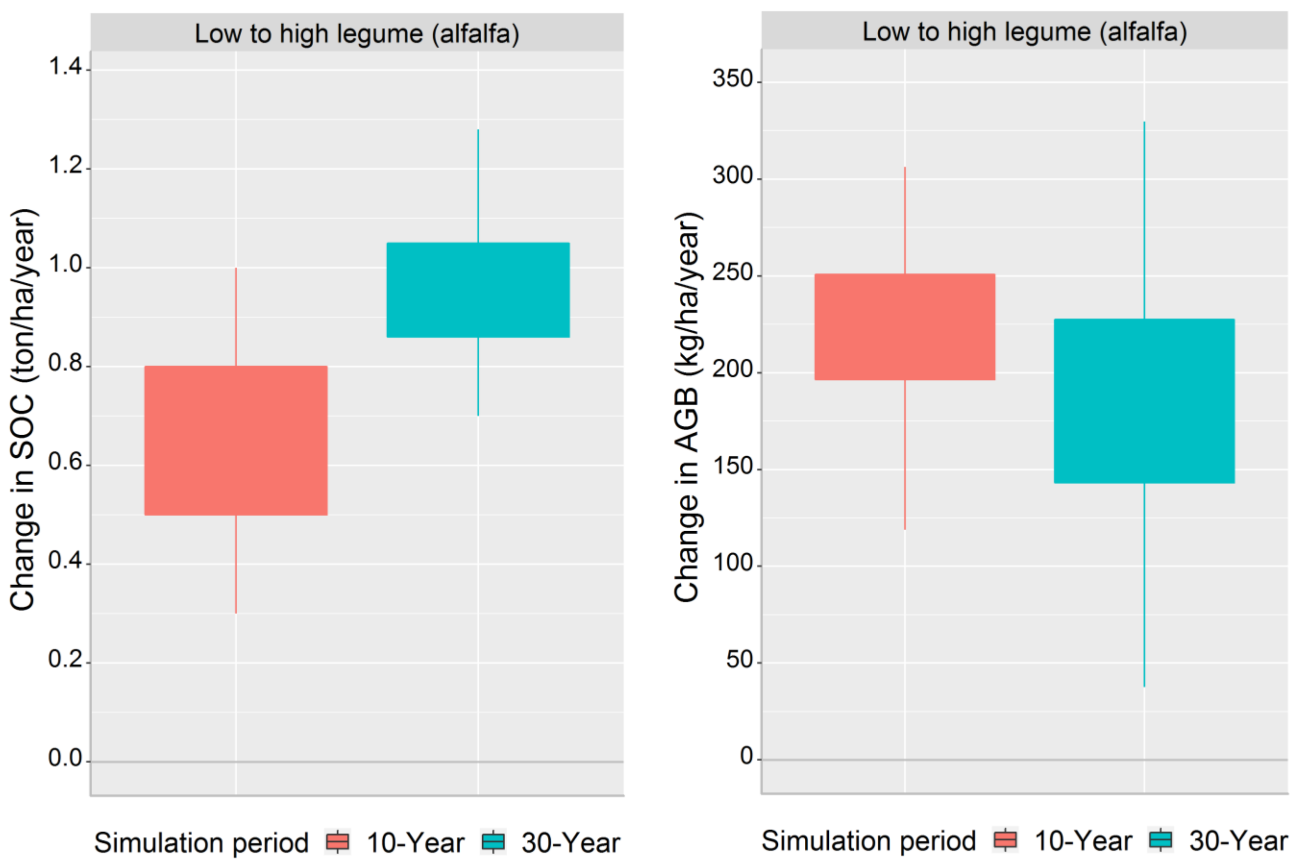


Fig. 7. Spatial variability in the response SOC (left) and AGB (right) to implemented pasture vegetation improvement scenario over 10-year and 30-year simulation periods (red and blue boxplots, respectively).

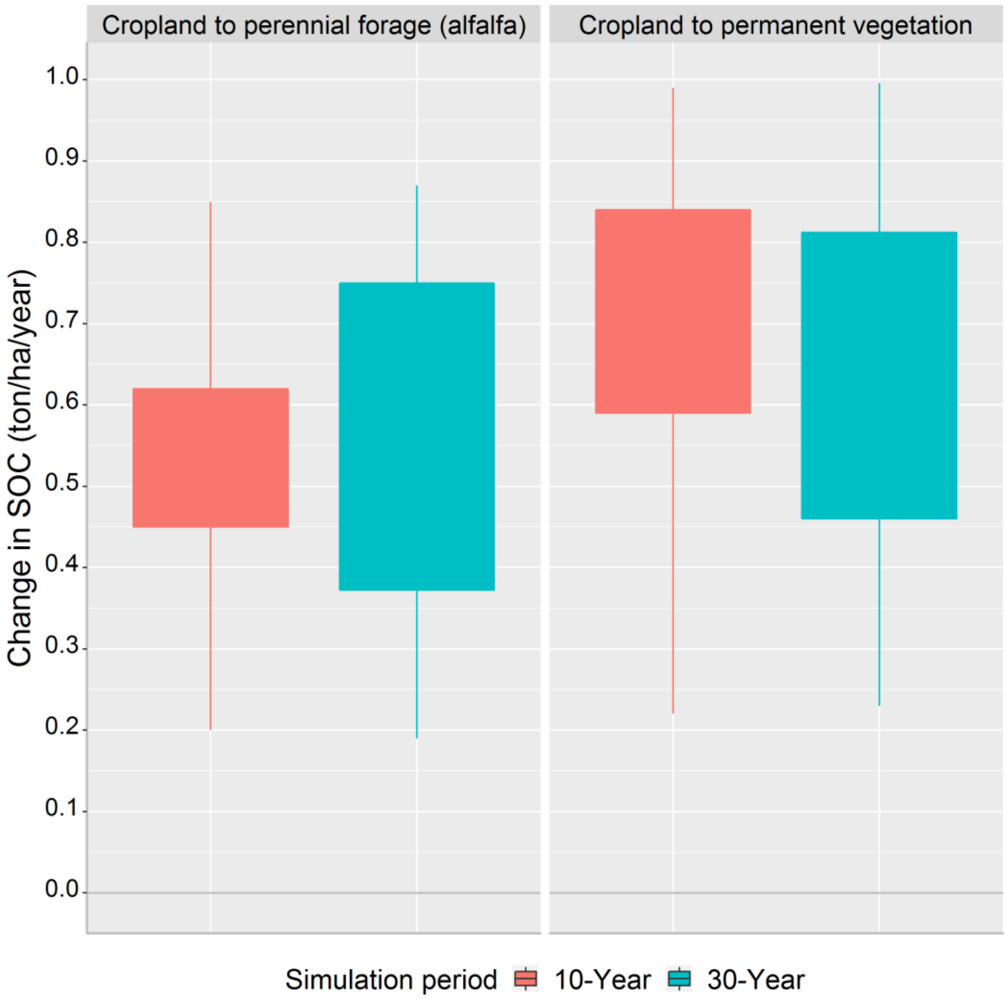


Fig. 8. Spatial variability in the response of SOC to implemented land conversion scenarios (vertical panels) over 10-year and 30-year simulation periods (red and blue boxplots, respectively).

4. Conclusion and implications

Land management choices are a primary means of adapting to changes in biophysical processes as a result of human disturbances and, in some cases, such choices can also enhance the provision of multiple ES (Howden et al., 2007). In other word, tradeoffs between agricultural production and various ES are not inevitable and that 'win-win' scenarios are possible (Power, 2010). It may be possible to manage agricultural lands to enhance the provision of multiple ES while still maintaining or enhancing the provisioning services that these lands were traditionally thought to produce (Christensen, 2004).

Despite the growth of market-based approaches to maintain carbon-related ES in agricultural lands, practical methods that account for shifting historical baseline (e.g., as a result of climatic changes) and additionality under local environmental and management conditions remain unresolved (Salzman et al., 2018). Due to spatial and temporal variability in the factors that determine the provision of carbon-related ES and diverse land management history across fields and landscapes, direct measurements of these ES are expensive and challenging, limiting the number of sites and management practices that can be examined. One common approach for assessing changes in the supply of carbon-related ES is to use look up tables created based on synthesizing results from previously published field studies on how changes in management practices affect the provision of carbon-related ES. However, land management practices are highly non-standardized and site-specific. Therefore, utilization of previous studies to assess potential supply of carbon-related ES from alternative land management practices in a given farm or region will result in substantial uncertainty that affects participation in ES programs and markets (Conant et al., 2011).

To address this data gap for Alberta's agricultural lands and support Alberta Agriculture Sector to explore opportunities for participating in ES programs and markets, we generated the information and science required to understand the potential supply of carbon-related ES from relevant land management choices. Using the CENTURY Ecosystem Model and historical land management practices, we developed spatially explicit organic carbon models for rangelands, pasturelands, and cropland of the IFC Watershed. We then used these carbon models to support better accounting of the historic supply of SOC and AGB, as well as gain and loss in SOC and AGB from a range of land management scenarios related to grazing management, pasture vegetation improvement and land conversion over a 10-year and a 30-year simulation period.

The results showed a pronounced variation in the historic supply of SOC and AGB in the IFC Watershed. Overall, the implementation of different land management scenarios resulted in a diverse range of gain or loss in SOC and AGB across the Watershed. The magnitude of gain or loss in SOC and AGB from the implemented land management scenarios varied among land-use types and simulation periods. Across the rangeland and pastureland of the Watershed, the response of SOC to the implemented grazing management scenarios was different from the response of AGB, while the implementation of vegetation improvement scenario in pasturelands resulted in a gain in both SOC and AGB. In addition, the implementation of land conversion scenarios in croplands resulted in a gain in SOC, but the magnitude of this gain in SOC was greater when the annual croplands were converted to permanent tame vegetation than to perennial forage. These findings collectively suggest that implemented land management scenario have the potential to maintain or even enhance the provision of SOC and AGB in Alberta's agricultural lands. However, potential gain or loss in these ES from the examined land management scenarios depends on the land use type, land management history, length of the implementation period, and last but not least local variability in ecosystem responses to particular management scenario. Therefore, cautious need to be considered in regards to proposing the examined land management scenarios as beneficial management practices across Alberta's agricultural lands. In other words, to increase the economic efficiency and participation to program and markets for carbon-related ES, special consideration needs to be paid to spatial heterogeneity in the response of carbon-related ES to a specific land management practice over short-term and long-term timescales.

The results of this study provide a strong foundation for assessing the current status of SOC and AGB in Alberta's agricultural lands. The information and knowledge developed provide a foundation to understand better market opportunities associated with conservation and restoration of the carbon-related ES in agricultural lands of the province. It also supports designing and developing innovative approaches to incentivize land management activities that encourage the provision of these two carbon-related ES. Although economic valuation was not done in this study, the modeling framework developed can be used as an important first step in a comprehensive cost-benefit analysis to measure gains or losses of carbon-related ES from alternative land management scenarios. Serving as a starting place, stakeholders can build on this information to explore various land management practices that potentially lead to long-term provision of carbon-related ES and resilient of socio-ecological systems in Alberta's agricultural lands. For example, lowering grazing intensity by decreasing the cattle stocking rate may reduce a rancher's income via the sale of beef cattle, but compensate or even increase it through the allocation of carbon credits. Therefore, determining how a rancher's total income would change in response to altering cattle stocking rate help understand better if implementing a lower grazing intensity level is an appropriate practice to maintain carbon-related ES in Alberta's agricultural lands.

Currently, information and knowledge developed through this project are being integrated into a decision support tool that includes a wider range of ES (e.g., water-related ES, biodiversity, and habitats) and land management scenarios (e.g., nutrient management). The ultimate goal is to develop credible and transparent market programs for protecting and enhancing multiple ES in Alberta's agricultural landscapes. Conservation markets for the provision of ecosystem services and biodiversity have the potential to benefit agriculture producers, the environment, and society. Information on the metrics and cost-benefit analysis can be used by industry in sustainability reporting, which expected to be based on credible science. The relevant industries can use the information generated from this study to make informed decisions in their business to be more competitive, environmentally friendly, and socially responsible.

5. Acknowledgments

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Appendix 1: Developing spatially explicit organic carbon models

CENTURY ecosystem model

We used the process-based plant-soil ecosystem model, CENTURY (v. 4.6; Parton et al., 1988; Parton et al., 1989). The CENTURY model was initially developed based on experiments in Great Plains grasslands (Parton et al., 1987), of which Alberta's grasslands is a northern extension. It has been extensively used to simulate SOC (e.g., Lugato et al. 2014) and AGB (e.g., Lopez-Marsico et al., 2015) across different terrestrial biomes and ecoregions, including Canadian Prairies (e.g., Van den Bygaart et al., 2008). The CENTURY model consists of several interactive submodels, including a sub-model for soil organic matter and a sub-model for plant growth. The major input variables for the CENTURY model include monthly climate data (e.g., rainfall and minimum and maximum temperature), soil properties (e.g., soil texture, depth, bulk density, drainage class and pH), atmospheric and soil nitrogen inputs, lignin content of plant material and land management information (e.g., grazing, fire; Parton et al., 1989). Additional details on the model structure and data needs are given in in Parton et al. (1987), Parton et al. (1988) and Parton et al. (1989).

Spatial modeling units

We used spatial data on land use, soil, topography, and land management to delineate unique spatial modeling units for simulation of SOC and AGB in the IFC Watershed. We first reclassified land use map of the Watershed (2010 version) into seven major land-use types (Table A1; Fig. A1), of which three land-use types of cropland, pastureland, and rangeland were considered for simulation of land management scenarios. The soil map of the Watershed (Fig. A1), which was developed by modifying the soil information from the Agricultural Region of Alberta Soil Inventory Database (AGRASID; Alberta Soil Information Centre, 2001), describes the spatial distribution of 12 soil types using 163 soil units at a scale of 1: 30,000 (Brierley & Bock, 2008). We intersected the soil map of the Watershed with the reclassified land-use layer (with seven major land-use types) to delineate all possible soil-land use units for the Watershed. We then eliminated the spatial units associated with two land-use types of "Water Body" and "Developed Land" from the soil-land use unit layer.

In addition, we dissolved the soil-land use units smaller than 0.5 hectares (e.g., along with the linear features such as roads) into adjacent units with the same soil and land use attributes. Topographic factors have been demonstrated to be among the key parameters responsible for determining the spatial and temporal distribution of precipitation and temperature that largely influence the provision of carbon-related ES (Hewins et al., 2018). Therefore, we used topographic data in the next step to decide on the adjacent spatial units with similar soil, land use, and management attribute that were fragmented by linear features (e.g., roads and railroads). First, we extracted elevation data for all the remaining spatial units in the soil-land use unit layer from the Digital Elevation Model (DEM) of the Watershed (spatial resolution of one meter). Then, we merged any of the two adjacent spatial units with similar soil, and land use attributes into a single spatial unit only if the similar pattern of variation in elevation (e.g., mean and interquartile range) was obtained across two units; otherwise, they were kept as two separate spatial units. 1011 soil-land use-topographic units were included in the final map that we considered as spatial modeling units for simulation of SOC and AGB in the IFC Watershed (Fig. A1).

Table A1. Detailed and reclassified (major) land-use types (2010) of the IFC Watershed.

Reclassified land-use types	Detailed Land use types	Area (%)
Crop Land	Barley, Oats, Wheat	38.0
Hay Land	Forage, Forage-Mix, Hay, Hay-Grass, Hay-Legume, Hay-Mix	16.2
Pasture Land	Grass, Pasture, Pasture-Grass, Pasture-Mix	15.3
Range Land	Grass, Range, Range-Grassland, Rangeland	21.2
Forest Land	Forest, Pasture-Woodland*	4.6
Developed Land	Acreage, Church, Dairy Farm, Farmyard, Roads, Railroad, Oil Well, Residential, Well Site	3.9
Water Body	Dugout, Forest-Wetland, Impoundment, Pasture-Wetland, Water, Waterway, Wetland, Wetland-Forest	0.8

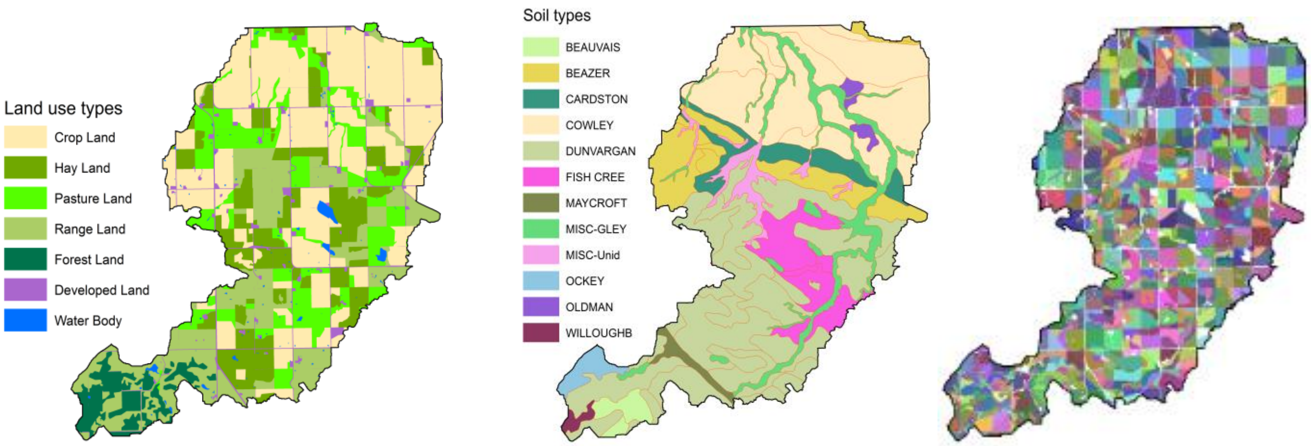
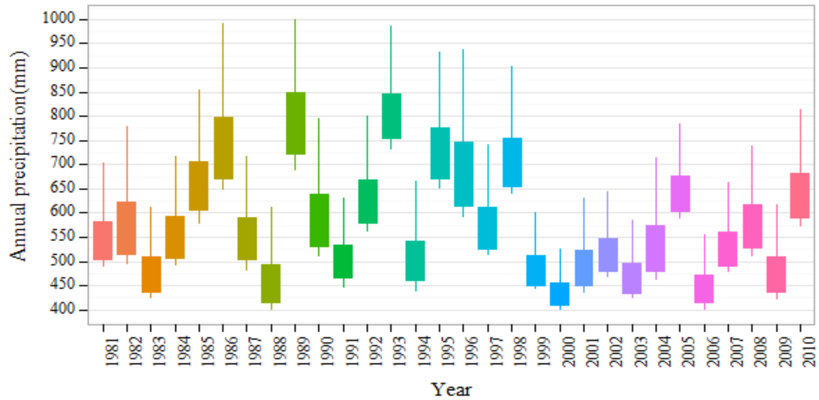


Fig. A1. Spatial distribution of land use (left), and soil types (middle) together with the spatial modeling units considered for simulation of SOC and AGB in the IFC Watershed. The red boundaries on the soil map (middle) show the area of spatial soil units in the Watershed (Brierley & Bock, 2008).

Initial model setup

We extracted climate data from ClimateNa_5.21 (Wang et al., 2012), which is a user-friendly interface that locally downscales historical and future monthly climate data layers into scale-free point estimates of climate values for the entire North American continent. For each spatial unit, we extracted time-series (1901-2010) of monthly precipitation and minimum and maximum mean temperature using geographic location information (center point of the unit) and median elevation data (all pixel values within the unit) extracted from the Digital Elevation Model (DEM) of the Watershed. We used actual monthly climate data for years 1901-2010, while long-term averages for this period were used for previous years (equilibrium or warm-up period). For each spatial unit, we also extracted mineral soil layers (depth and drainage class) and associated soil properties data (texture, bulk density, rock content, pH) from the soil database of the Watershed (Brierley & Bock, 2008).

To initially set up the model, we considered an equilibrium or warm-up period followed with two time periods demonstrating more recent management history of the western Canadian agricultural lands (Wang et al., 2014). First, we ran a 4900-year period (3000 BC to 1900 AD) of combined bison grazing (a two-month bison grazing event shifting annually by two months) and fire event (every six years; Wang et al., 2014) using long-term climate averages to reach equilibrium levels of AGB and SOC under a natural disturbance regime (Parton et al., 1988). Next, we ran a 60-year period (1901-1960) of high cattle grazing intensity during the snow-free months (mid-April to mid-October; Wang et al., 2014) using actual monthly weather records. For pastureland and rangeland, we then ran a 50-year period (1961-2010) of cattle grazing using spatially-explicit information on historical grazing practices (season and intensity) collected from native ranges and pastures of the Watershed during years of 2000– 2010 by the Alberta Agriculture and Forestry. For cropland, we ran this 50-year period using spatially-explicit information on historical agricultural practices (cultivation method, fertilizer application) collected from the Watershed during years of 2000 – 2010 by the Alberta Agriculture and Forestry.



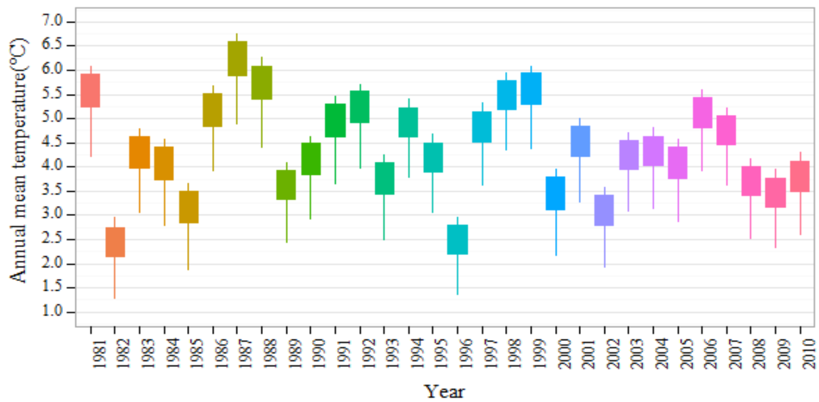


Fig. A2. Long-term variation (1981 to 2010) in annual total precipitation (top) and mean temperature (bottom) in the IFC Watershed. Climate data were extracted from ClimateNa_5.21 (Wang et al., 2012). Boxplots show variation across 1011 units delineated for simulation of SOC and AGB in the Watershed.

We ran the CENTURY model with the coupled C-N-P sub-models, which simulate carbon flows under the condition that no other elements than nitrogen and phosphorous could become a limiting factor for carbon flows (Parton et al., 1988). For the simulation of rangeland, we tested three different types of model parameter value sets (Fig. A3). These were: (1) default vegetation parameter values for temperate, C3 grasslands from the CENTURY model, (2) suggested parameter values for Alberta's temperate, C3 grasslands (based on consultations with CENTURY Core Group at Colorado State University), and (3) the most representative sets of parameter values for the black soils of the Foothills Fescue grasslands that were obtained through an extensive parameterization and calibration of the CENTURY model based on range intervals of physically and biologically meaningful parameter uncertainty ranges with equal probability (Iravani et al., 2019). Additional details on the CENTURY model set up and parameterization and calibration are given in Iravani et al. (2019).

For the simulation of pastureland and cropland, we used the same three types of model parameter value sets during the warm-up period and the following 60-year period (Fig. A4). However, for the simulation of pastureland during the last 50-year period, we also incorporated default vegetation parameter values for perennial legumes (alfalfa). Finally, for the simulation of cropland during the last 50-year, we only used default crop parameter values for barley as the dominant crop in the Watershed (Parton et al., 1988).

Model performance evaluation

We evaluated model performance for two land-use types of pastureland and rangeland. We obtained remotely-sensed AGB proxies based on the 16-day composite MODIS (Moderate Resolution Imaging Spectroradiometer) NDVI time series for the entire growing seasons of 2000-2010 period from the Land Processes Distributed Active Archive Center (LP DAAC; https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13q1_v006). We extracted AGB proxies for each spatial modeling unit. Though, due to the spatial resolution of NDVI data (250 m spatial resolution), no proxy measure of AGB was extracted for the smaller-sized spatial modeling units. We used the Pearson's correlation analysis (R v. 3.1.1; R Development Core Team, 2017) to evaluate the association between time series of simulated AGB and the corresponding time series of remotely sensed AGB proxies for growing season 2000-2010 (Fig. A3, Fig. A4). Finally, we selected the model runs with the most desirable performance (e.g., a greater yearly correlation between simulated AGB and remotely sensed AGB proxies; Iravani et al., 2019) to quantify historic supply of SOC and AGB (Fig. A5) and to simulate impacts from relevant land management scenarios.

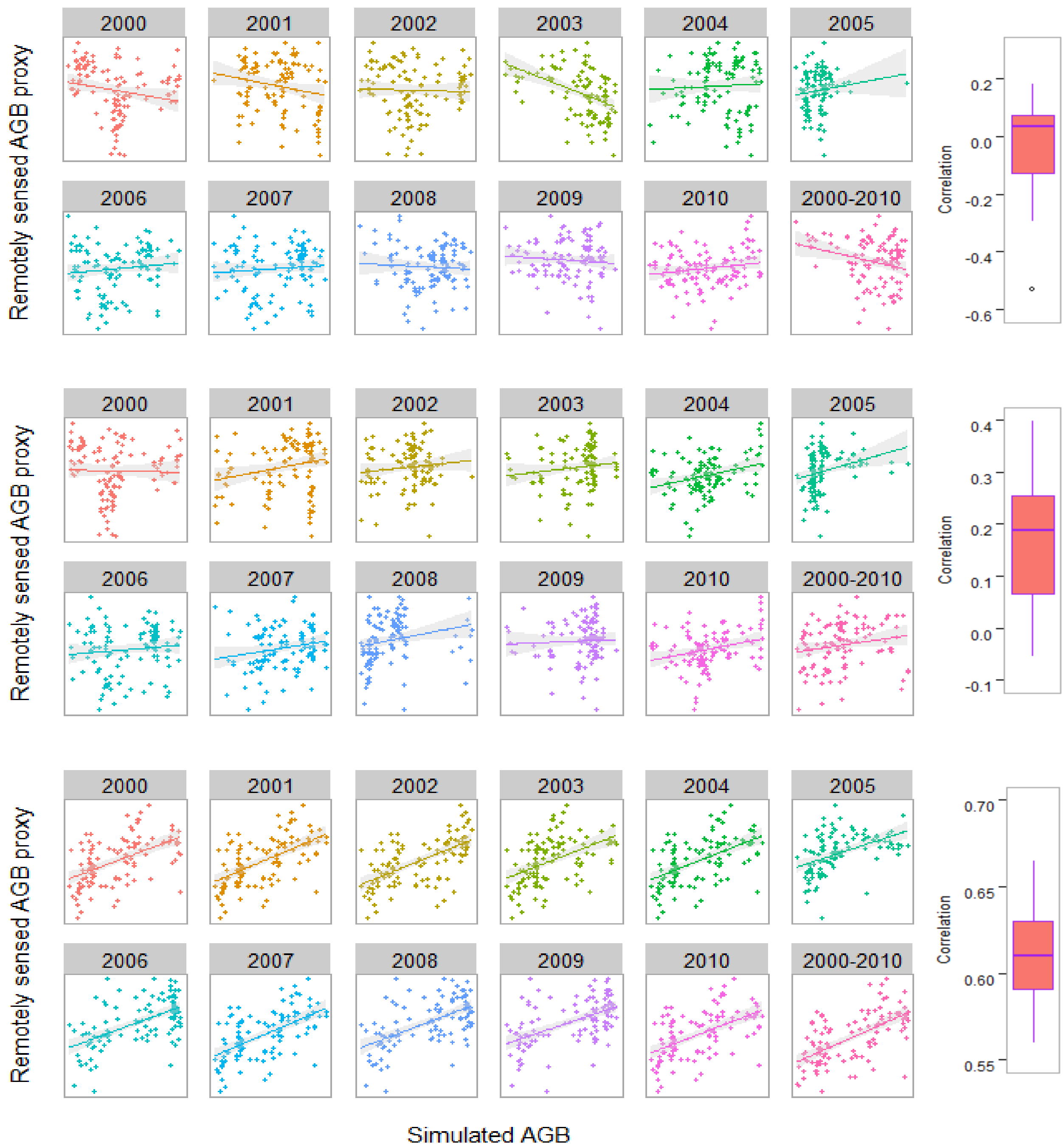


Fig. A3. Comparison of simulated AGB with the corresponding remotely sensed AGB proxies (2000 to 2010) in spatial units associated with rangelands. The simulation results obtained based on default parameter values for temperate, C3 grasslands (top), suggested parameter values for Alberta's grasslands (middle), and optimized parameter value sets for black soils of the Foothills Fescue grasslands (bottom). For the later parameter set, median values of the best simulation runs were used (bottom). The 2000-2010 panels show average data for the period 2000 to 2010. Boxplots show inter-annual variation (from 2000 to 2010) in correlation among simulated AGB and remotely sensed AGB proxies.

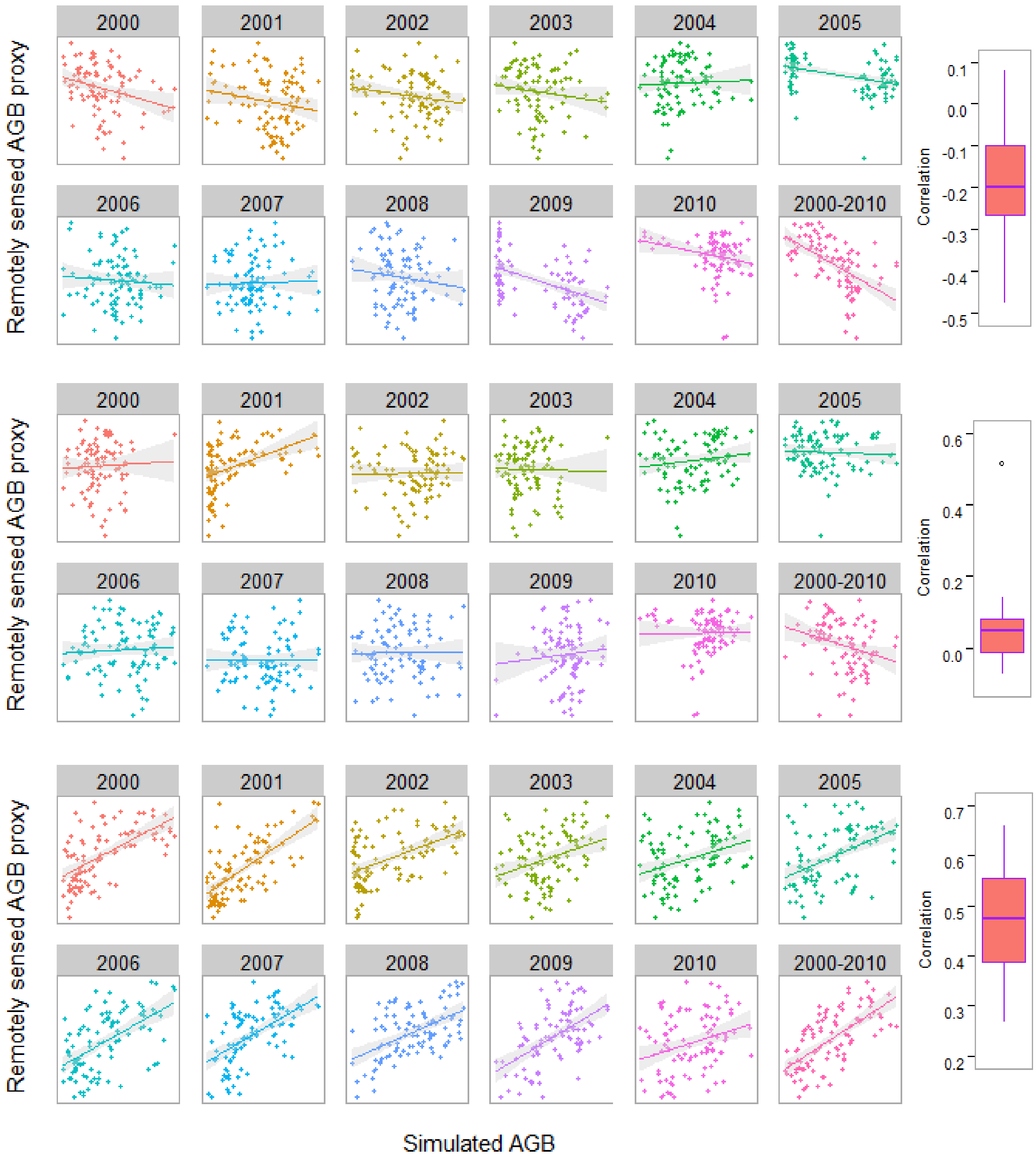


Fig. A4. Comparison of simulated AGB with the corresponding remotely sensed AGB proxies (2000 to 2010) in spatial units associated with pasturelands. The simulation results obtained based on the incorporation of default parameter values for permanent legumes with the: default parameter values for temperate, C3 grasslands (top), suggested parameter values for Alberta's grasslands (middle), and optimized parameter value sets for black soils of the Foothills Fescue grasslands (bottom). See Fig. 4 for further descriptions of the plots.

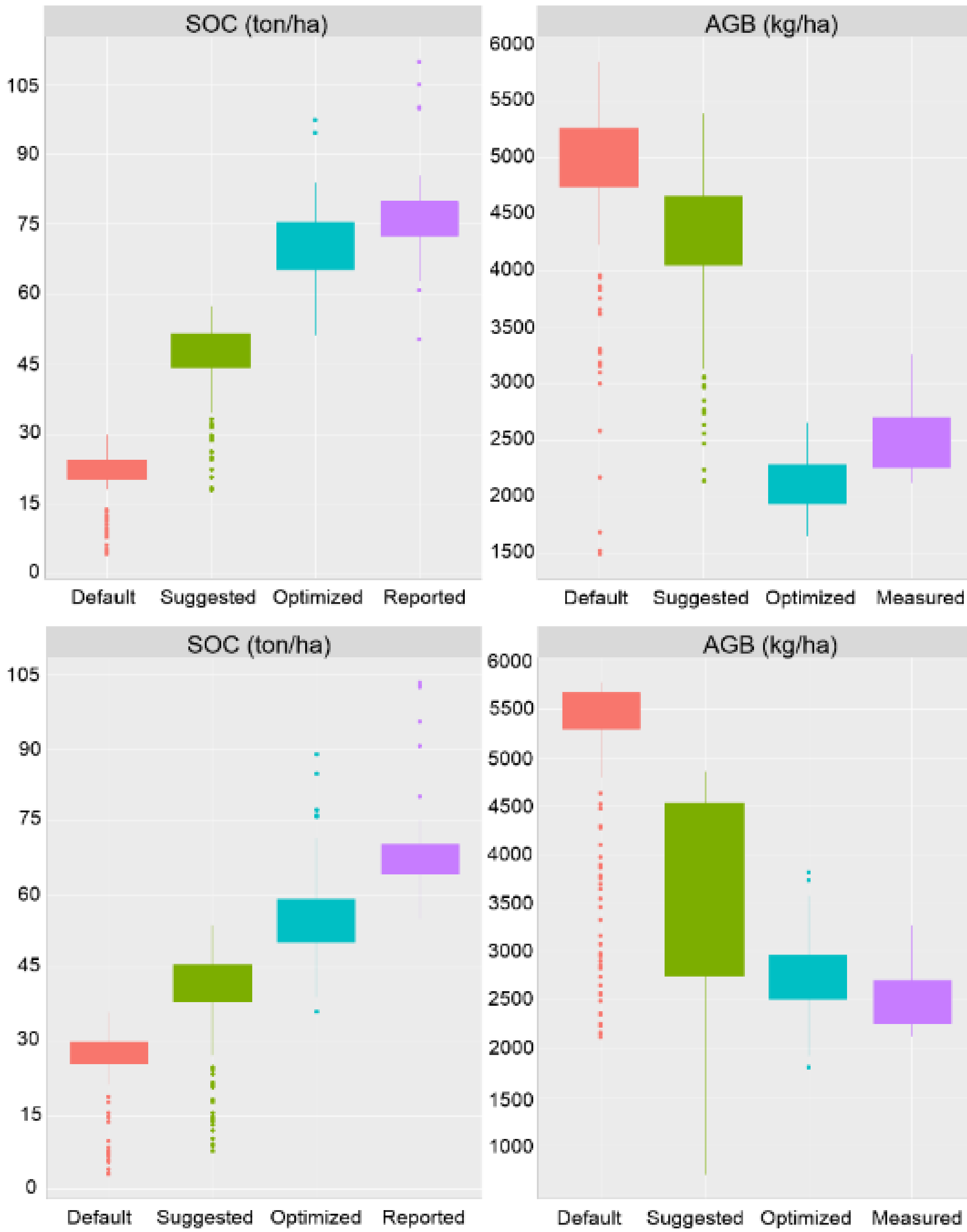


Fig. A5. Comparison of simulated results of SOC (left panels) and AGB (right panels) for rangeland (top row) and pastureland (bottom row) with the SOC data obtained from the AGRASID (Alberta Soil Information Centre, 2001) soil units in the IFC Watershed and AGB measurements from Rangeland Reference Areas (RRA) spaced throughout the Foothills Fescue Natural Sub-region (AEP, 2015). The simulation results obtained based on default parameter values for temperate, C3 grasslands ("Default"), suggested parameter values for Alberta's grasslands ("Suggested"), and optimized parameter value sets for black soils of the Foothills Fescue grasslands ("Optimized"). For the later parameter set, the median values of the best simulation runs were used.

Appendix 2: Impacts of land management scenarios

We evaluated the potential supply of SOC and AGB from the land management scenarios related to grazing management, pasture vegetation improvement, and land conversion. Details of simulated land management scenarios are as follow:

Grazing management

Based on consultation with local experts and by reviewing relevant literature (e.g., Blanchet et al., Popp et al., 2000; 2000; Howery et al., 2001; Saskatchewan Agriculture, Food and Rural Revitalization, 2002; Alberta Beef Producers and Alberta Agriculture and Forestry, 2006; Briske et al., 2008; Aasen et al., 2009; Meehan et al., 2011; Teague et al., 2011; Teague et al., 2013; Alberta Environment and Park, 2015; MULTISAR, 2015; Conant et al., 2017; Gourlez de la Motte et al., 2018), we proposed grazing management scenarios as a combination of grazing season (or timing of grazing) and grazing intensity (or density of grazing) scenarios (Table A2). Due to the model's monthly simulation time step, we altered timing of grazing based on a minimum period of a month, though this time period may not be an appropriate time window for designing the length of grazing and rest periods in some of the proposed grazing management scenarios (e.g., rotational grazing, short season grazing, and deferred grazing).

In our simulation, the "historic grazing" characterized as a combination of "historic grazing season" representing historical timing of grazing, and "historic grazing intensity" representing historical grazing intensity implemented in the Watershed. First, we simulated a "no grazing" scenario by removing all historic grazing events. We also simulated a 10% lower grazing intensity scenario by considering historic grazing season. We then simulated the proposed grazing season scenarios under the historic grazing intensity as well as under a 10% lower grazing intensity scenario relative to the historic grazing intensity. However, for short season grazing season scenario, we carried out the simulation under the historic grazing intensity as well as under a 20% lower grazing intensity scenario relative to the historic grazing intensity. Details of grazing management scenarios are as below.

No grazing

We proposed this scenario for conservation and sustainable use of natural areas, including areas covered with riparian vegetation. For a given spatial modeling unit, we completely banned livestock grazing during the simulation periods (10- and 30-year; Table A2).

Low grazing

We proposed this scenario for areas covered with rangeland and pastureland vegetation. During the simulation periods (10- and 30-year), we implemented the same grazing schedule as historic grazing season in a given spatial modeling unit, but we lowered grazing intensity on average by 10% relative to the historic grazing intensity to protect the ecosystem from grazing impacts (Table A2).

Short season grazing

We proposed this scenario for conservation and sustainable use of natural areas, including areas covered with riparian vegetation. In our simulation, we restricted livestock grazing in a given spatial modeling unit to July and August during the simulation periods (10- and 30-year) to protect the ecosystem from grazing impacts in spring/early summer and late summer/fall (Table A2).

Summer rotational grazing

We proposed this scenario for areas covered with rangeland, pastureland, and riparian vegetation. This scenario was repeated every two years during the simulation periods (10- and 30-year). We restricted livestock grazing in a given spatial modeling unit (considered as a paddock) to the months of June and August (twice-over rotation) in one year and the months of July and September in the other year to allows ecosystem to rest and recover between grazing events (months of July and August, respectively), and also graze at different times of the year during the simulation periods (Table A2).

Deferred rotation grazing

We proposed this scenario for areas covered with rangeland and pastureland vegetation. This scenario was repeated every four years during the simulation periods (10- and 30-year). Each year, we delayed livestock grazing in a given spatial modeling unit (considered as a paddock) and started at a different month during the growing season which was continued until September (end of the growing season). These were four months of June (first year), July (third year), August (fourth year) and September (second year), approximately representing the periods that vegetation is actively growing, flowering, setting seed and starting senescence, respectively (Table A2). Delay in grazing helps vegetation to pass through critical phenological stages and provide vegetation with the opportunity to periodically recover from grazing impacts, and possibly set seed.

Short duration deferred rotation grazing

We proposed this scenario for areas covered with rangeland, pastureland, and riparian vegetation. This scenario was repeated every four years during the simulation periods (10- and 30-year). Each year, we delayed and restricted livestock grazing in a given spatial modeling unit (considered as a paddock) to a different month during the growing season to protect vegetation from long-season grazing and also to avoid grazing at the same time of the year. These were four months of June (first year), July (third year), August (fourth year) and September (second year), approximately representing the periods that vegetation is actively growing, flowering, setting seed and starting senescence, respectively (Table A2). Delay and restriction of grazing help vegetation to pass through critical phenological stages and provide vegetation with the opportunity to periodically recover from grazing impacts, and possibly set seed.

Rest rotation grazing

We proposed this scenario for areas covered with rangeland and pastureland vegetation. This scenario was repeated every five years during the simulation period (10- and 30-year). Similar to deferred rotation grazing scenario, we delayed and started livestock grazing in a given spatial modeling unit (considered as a paddock) at a different month during growing season which was continued until September (end of growing season), but we included an additional yearlong rest period from livestock grazing during the third year of each simulation round to allow the ecosystem to recover from grazing impacts (Table A2).

Short duration rest rotation grazing

We proposed this scenario for areas covered with rangeland, pastureland, and riparian vegetation. This scenario was repeated every three years during the simulation period (10- and 30-year). We restricted livestock grazing in a given spatial modeling unit (considered as a paddock) to June and July (early summer) in one year and the months of August and September (late summer) in the other year followed with a yearlong rest period from livestock grazing during the third year of each simulation round to allow ecosystem to recover from grazing impacts (Table A2).

Table A2. Details of proposed grazing management scenarios. Scenarios with grazing event were simulated under historic grazing intensity and a 10% lower grazing intensity scenario, except for short season grazing scenario that was simulated under a 20% lower grazing intensity relative to historic grazing intensity.

Grazing season scenario	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
No grazing	1												
Low grazing	Varied	The historic grazing season											
Short season grazing	1												
Summer rotational grazing	1												
	2												
Deferred rotation grazing	1												
	2												
	3												
	4												
Short duration deferred rotation grazing	1												
	2												
	3												
	4												
Rest rotation grazing	1												
	2												
	3												
	4												
	5												
Short duration rest rotation grazing	1												
	2												
	3												

Pasture vegetation improvement

We proposed this scenario to improve plant species composition in pastureland vegetation using perennial legume forage species. The scenario was repeated every six years during the simulation periods (10- and 30-year). At the beginning of each simulation period, we converted land in a given spatial unit from existing pastureland vegetation to a perennial tame vegetation type with at least 50% legume cover (alfalfa). We then rested the spatial unit (considered as a paddock) from livestock grazing for a complete growing season and moderately grazed (50% of AGB removed) for the next five years under relevant grazing scenarios (see section 1 above).

Land conversion

We proposed this group of scenarios for the conversion of land areas under cultivation by annual crops (croplands) to perennial forage or permanent vegetation. The perennial forage scenario was repeated every six years during the simulation periods (10- and 30-year). At the beginning of simulation periods (10- and 30-year), we converted land in a given spatial modeling unit from annual crop (barley) to perennial forage (alfalfa) vegetation. We then rested the spatial unit (considered as a paddock) from livestock grazing for a complete growing season and moderately grazed (50% of AGB removed) for the next five years under relevant grazing scenarios (see section 2.6.1). For the permanent vegetation scenario, at the beginning of simulation periods (10- and 30-year), we converted land in a given spatial modeling unit from annual crop (barley) to permanent vegetation. We then rested the spatial unit (considered as a paddock) from livestock grazing for one year and moderately grazed (50% of AGB removed) for the rest of simulation periods under relevant grazing season scenarios (see section 1 above).

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