Published online December 22, 2017

Journal of Environmental Quality SPECIAL SECTION

PREDICTING SOIL ORGANIC CARBON IN AGROECOSYSTEMS UNDER CLIMATE CHANGE

Climate Change Impacts on Yields and Soil Carbon in Row Crop Dryland Agriculture

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Abstract

Dryland agroecosystems could be a sizable sink for atmospheric carbon (C) due to their spatial extent and level of degradation, providing climate change mitigation. We examined productivity and soil C dynamics under two climate change scenarios (moderate warming, representative concentration pathway [RCP] 4.5; and high warming, RCP 8.5), using long-term experimental data and the DayCent process-based model for three sites with varying climates and soil conditions in the US High Plains. Each site included a no-till cropping intensity gradient introduced in 1985, with treatments ranging from wheat–fallow (*Triticum aestivum* L.) to continuous annual cropping and perennial grass. Simulations were extended to 2100 using data from 16 global circulation models to estimate uncertainty. Simulated yields declined for all crops (up to 50% for wheat), with small changes after 2050 under RCP 4.5 and continued losses to 2100 under RCP 8.5. Of the cropped systems, continuous cropping had the highest average productivity and soil C sequestration rates (78.1 kg C ha^{-1} yr^{-1} from 2015 to 2045 under RCP 4.5). Any increase in soil C for cropped rotations was realized by 2050, but grassland treatments increased soil C (up to 69%) through 2100, even under RCP 8.5. Our simulations indicate that reduced frequency of summer fallow can both increase annualized yields and store more soil C. As evapotranspiration is likely to increase, reducing fallow periods without live vegetation from dryland agricultural rotations may enhance the resilience of these systems to climate change while also increasing soil C storage and mitigating carbon dioxide emissions.

Core Ideas

- Soil C sequestration rates increased with cropping intensity.
- Water-limited systems will see increased yield losses under climate change.
- Intensive systems retained soil C but with more variability under climate change.
- Grasslands are likely to sequester more soil C than annual cropping systems.

Agroecosystem soils across the globe have experienced considerable erosion and organic matter losses as crop productivity is often prioritized over soil health (Govers et al., 2017). While declining soil organic matter (SOM) is not a new concern (Stewart and Hirst, 1914), the potential for agricultural soils to help mitigate climate change through soil carbon (C) storage has renewed interest in SOM management (Paustian et al., 2016; Powlson et al., 2016). Management practices that align with the tenets of conservation agriculture (i.e., minimizing soil disturbance, increasing soil cover, and increasing crop diversification) have been shown to build and maintain SOM, while also maintaining agronomic yields (Knowler and Bradshaw, 2007; García-Torres et al., 2013).

Globally, semiarid regions constitute between 15 and 20% of the Earth's land surface and are home to nearly a billion people (Bot et al., 2000; Reynolds et al., 2007). Most agricultural land in these regions is not irrigated due to scarce water sources, and dryland, nonirrigated, agriculture is the dominant agricultural management system. To cope with uncertain and scarce precipitation, dryland farming in North America has historically implemented tilled, bare fallow periods to accumulate rain water in the soil for the next crop. With the advent of no-till agriculture, these fallow periods are increasingly maintained without living vegetation through the application of herbicides rather than tillage. However, studies show that the 14-mo fallow periods (herein referred to as *summer fallow*) common between dryland winter wheat (*Triticum aestivum* L.) crops in North American agroecosystems can store a maximum of 40% of the precipitation received during the year even under no-till management (Peterson et al., 1996). While this summer fallow stabilized yields, it also reduced soil quality and C stocks (Rasmussen et al., 1980; Peterson et al., 1993). In the Great Plains, 40 yr of cultivation with a winter wheat–fallow (WF) rotation reduced soil organic C (SOC) by 41, 34, and 25% in 0- to 15-, 15- to 30-, and 30-to 45-cm soil layers, respectively, relative to uncultivated soils (Haas et al., 1957). Hence, the fallow periods maintained

J. Environ. Qual.
doi:10.2134/jeq2017.08.0309

Supplemental material is available online for this article.
Received 7 Sept. 2017.
Accepted 25 Nov. 2017.
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Abbreviations: CC, continuous cropping; ET, evapotranspiration; GCM, global circulation model; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; NASS, National Agricultural Statistics Service; NT, no-till; PUE, precipitation use efficiency; RCP, representative concentration pathway; SOC, soil organic carbon; SOM, soil organic matter; WCF, wheat–corn–fallow; WCM, wheat–corn–millet; WCMF, wheat–corn–millet–fallow; WF, wheat–fallow; WWCM, wheat–wheat–corn–millet.

without living vegetation, as used in the semiarid systems described in this study, can have opposite effects on SOC to the fallow periods that allow natural revegetation to restore soil nutrients and SOC, as is often defined in humid, tropical systems (Szott et al., 1999).

Many studies have evaluated the precipitation use efficiency (PUE) associated with different management strategies in dryland agroecosystems (Peterson et al., 1996; Nielsen et al., 2005; Deng et al., 2006; Sherrod et al., 2014), with a focus on maximizing crop production. For example, Peterson and Westfall (2004) reported that replacing summer fallow with crops can double crop residue production and increase annualized grain yields relative to WF. Research that centers on improving SOM in these systems is less common (cf. Sherrod et al., 2003), even though yields and soil C are intrinsically linked through the positive association between SOM and soil quality (e.g., buffering capacity, nutrient retention, soil water holding capacity, enhanced aggregation/soil structure, and support for biological functions/communities (Wall and Bardgett, 2012)). Due to these feedbacks, it is important to include an assessment of both SOC and crop production when evaluating a given management strategy (Halvorson et al., 2002; Sainju et al., 2009), especially when evaluating potential system responses to climate change.

The increased temperatures and altered precipitation patterns associated with climate change are predicted to have severe consequences for yields (Zhao et al., 2017) and SOM (Thomson et al., 2006); this may be especially true in dryland agroecosystems already facing the constraints of water limitation (Huang et al., 2016). However, due to the positive association with nutrient retention and water holding capacity, soils with a higher SOM content can be more resilient to the impacts of climate change such as increased droughts (Letter et al., 2003). Consequently, while maximizing yields will always remain a producer's priority, there are longer-term agricultural benefits associated with increasing SOC as well. One management option shown to both build SOM and enhance row crop production in North American, semiarid regions is increased cropping intensity (i.e., reduced time in summer fallow) (Sherrod et al., 2003; Campbell et al., 2005; Sherrod et al., 2014). However, the performance of these intensified cropping systems in the face of climate change is unclear. Using ecosystem models validated by long-term data, predictions can be made about optimal crop selection and management options given expected climate change.

Dynamic ecosystem models use site and management input data to predict how pools of an element will change over time; most focus on carbon and nitrogen dynamics (e.g., Rosenzweig et al., 2013; Vereecken et al., 2016). In recent years models have been used to predict the interaction between climate change and agriculture, reporting impacts on crop yields (Deryng et al., 2011; Tatsumi et al., 2011; Rosenzweig et al., 2014), soil C stocks (Parton et al., 1995; Jones et al., 2005; Thomson et al., 2006) and greenhouse gas (GHG) emissions (Lee and Six, 2010; Valin et al., 2013) under varying land management options and climate change scenarios. However, few studies specifically focus on SOM in nonirrigated dryland agroecosystems (although see Paustian et al., 1996; Thomson et al., 2006). With growing populations dependent on agriculture in water-limited regions (Reynolds et al., 2007; FAO, 2008; Huang et al., 2016), there is a growing need to improve predictions of climate change impacts to these systems. Furthermore, since SOM is integral to soil health and, ultimately, crop productivity (Allison, 1973; Reeves, 1997; Pan et al., 2009), modeling efforts need to ensure accurate responses of SOM to different management practices. Although process-based ecosystem-scale models are simplified abstractions of the complex feedbacks between SOM, plant growth, and climate, they also provide us with the most reliable predictions of how we can manage agroecosystems to build and maintain SOM while ensuring viable crop yields in the face of climate change.

Using both measured and modeled data, we aimed to identify how reduced summer fallow impacts soil C sequestration in dryland agroecosystems responding to the forecasted changes in climate. To achieve this aim we addressed two main objectives: (i) to quantify C inputs to topsoil (0–20 cm) under no-till (NT) dryland agroecosystems with different cropping intensity, and (ii) to determine how climate change and cropping intensity will interact to influence net changes in SOC over the coming century. Simulating three sites across Colorado, the DayCent process-based model was calibrated and validated using 24 yr of measured yield data (1985–2009) from four major crops (winter wheat; corn [*Zea mays* L.]; grain sorghum [*Sorghum bicolor* (L.) Moench]; and millet [*Panicum miliaceum*]) and used to predict C inputs to soils below different cropping systems. Using this calibration, we estimated changes in grain and stover yields from each of the crops as the climate changes over the 21st century. The simulated changes in total topsoil C stocks were used to determine net soil C sequestration rates beyond the present day under two different climate change scenarios, moderate warming (representative concentration pathway [RCP] 4.5) and high warming (RCP 8.5). We hypothesized that as temperatures increased, crop yields would decline and soil decomposition would increase, generally reducing SOC as the century progressed. However, increased cropping intensity would also result in increased C inputs to the soil per unit time and therefore promote net C sequestration.

Materials and Methods

Study Sites and Historical Management

Three experimental sites were initiated in 1985 to evaluate different dryland, NT cropping systems in eastern Colorado. This Dryland Agroecosystem Project included gradients of (i) evapotranspiration (ET) between three sites (Sterling, CO [low]; Stratton, CO [medium]; Walsh, CO [high]), (ii) soil conditions at three catena positions at each site (summit, sideslope, toeslope), and (iii) crop intensity at each site ranging from fallow every other year to continuous cropping (see Supplemental Fig. S1). Further details of the experimental design and rationale can be found in Peterson et al. (1993) and Sherrod et al. (2014). Basic site information is summarized in Supplemental Table S1, and further information is presented in Sherrod et al. (2014).

All three locations were initially (pre-1900) shortgrass steppe that makes up most of the North American Great Plains. Fire and grazing are known to have played a central role in forming the shortgrass steppe (Wells, 1970; Anderson, 2006), likely maintaining this vegetative regime until human intervention (Axelrod, 1985). When the experiment began in 1985, the sites had been in a conventional, tilled WF rotation for at least 50 yr, but the exact date that cultivation began is unknown.

Cropping Systems and Experimental Management

Each experimental site ceased tillage in 1985, and comparative NT treatments were initiated. Treatments varied the amount of time in summer fallow, including WF, wheat–corn–fallow (WCF), wheat–corn–millet–fallow (WCMF), and continuous opportunity cropping (CC), where summer fallow was eliminated and each year a crop was chosen according to market demands. In order of frequency, corn, grain sorghum, wheat, millet, sunflower (*Helianthus annuus* L.), Austrian winter pea (*Pisum sativum* L.) and soybean [*Glycine max* (L.) Merr.] were grown in the CC rotation between 1985 and 2009 (Supplemental Table S2). The WCF and CC treatments have remained consistent since 1985, but the WF and WCMF treatments used from 1985 to 1997 were changed to wheat–corn–millet (WCM) and wheat–wheat–corn–millet (WWCM) between 1998 and 2009, respectively. At the site furthest south (Walsh), all instances of corn in the WCF, WCMF, WCM, and WWCM treatments were replaced by grain sorghum. Two replicates of all entry points of the rotations are present at each site, equaling a total of 20 cropped strips per location (i.e., 2× wheat–fallow, 2× fallow–wheat, etc.). Detailed timeline management information of the rotations at each site is provided in Supplemental Fig. S1 and Supplemental Table S2.

In addition to the rotations of increasing cropping intensity (where 0 = 0% of years cropped and 1.0 = 100% of years cropped [i.e. no summer fallow]; WF, 0.5 intensity; WCF, 0.67 intensity; WCMF, 0.75 intensity; WCM/WWCM/CC, 1.0 intensity), a perennial grass treatment was established in spring 1986 with a seed mixture representing the major USDA Farm Service Agency Conservation Reserve Program species at the time. Starting in 1990, these grass strips were harvested to represent moderate grazing that would occur on native plains of this type.

Fertilizer nitrogen and phosphorus were applied to all cropped rotations at planting according to soil tests performed at each site. See Supplemental Material for further information.

Experimental Sampling

Crop yields and total aboveground biomass were collected from each site, slope, and strip each year. Aboveground grain and stover biomass was corrected for moisture and determined for all unique locations for the experimental period of 1985 to 2009.

Soils at all locations (strips, slopes, and sites) were sampled twice during the initial 24-yr experimental period (spring 1986 and fall 1997) as well as once in fall 2015 to provide an additional time point for comparison to model-simulated values. Soils were sampled to 20-cm depth, divided and composited into four increments (0 to 2.5 cm, 2.5 to 5 cm, 5 to 10 cm, 10 to 20 cm), processed, and analyzed for SOC as described in Sherrod et al. (2002). Bulk density measurements were collected for each site, slope, and strip combination (n = 198) for each depth increment in 1989, 1997, 2005, and 2009, with no significant change after 1997. Consequently, soil C stocks of 1986 were calculated using 1989 bulk density measurements and stocks of 1997 and 2015 were both calculated using 1997 bulk density measurements.

Model Initialization and Initial Parameterization

The DayCent model (Parton et al., 1998; Zhang, 2016; see Supplemental Material) was initialized assuming native grassland at all sites until 1900, followed by tilled WF systems up to 1985, where predicted yields were matched to those measured by published studies during this time (Rasmussen and Parton, 1994; Schillinger and Papendick, 2008). To ensure the model accurately reflected soil C stocks at each site, the predicted values were compared with 1986 measurements. Initially, two of the simulated sites overpredicted the soil C stocks (by up to 20%), so the productivity of the native grasses grown (until 1900) at each site was reduced to match measured data (model parameter PRDX reduced from 0.065 to 0.03 at Stratton and 0.02 at Walsh—grassland productivity estimates were still well within measured ranges for the semiarid High Plains). While C saturation dynamics (Six et al., 2002; Stewart et al., 2007) are not explicitly represented by the model, this was not considered a concern at our sites given their level of saturation deficit (see Supplemental Material). Due to different measured soil conditions of the slope positions at each site (Supplemental Table S1), each was simulated as a unique location nested within site (n = 9). Weather data for the model was derived from the PRISM dataset of 1980 to 2010 daily temperature and precipitation values specific to the coordinates of each site (PRISM Climate Group, 2015).

Calibration and Validation of Experimental Crop Rotations

To ensure DayCent simulated C inputs to the soil accurately, annual aboveground biomass production was compared with measured yield data from each site. This consisted of modifying key crop production parameters (Supplemental Table S3) using two steps: (i) independent calibration and (ii) site-specific calibration (see Supplemental Material for more information). After new crop production parameter values were set, each slope position (n = 3) of each rotation treatment (including grass, n = 11) of each site (n = 3) was simulated individually from 1985 to 2009 using management information (crop type, fertilizer amount, planting date, and harvest date). To replicate the experimental design and allow direct comparison to measured data, the WF and WCMF strips were changed to WCM and WWCM, respectively, for the duration of the second 12-yr experiment phase (i.e., 1997–2009).

Simulation of Climate Change Scenarios to 2100

Simulations of each unique slope, rotation treatment, and site (n = 99) were extended from 2009 to 2100, switching the experimental rotations back to those initiated in 1985 (WF, WCF, WCMF, CC, and grass; Supplemental Fig. S1). These were deemed to represent a better cropping intensity gradient (0.5 to 1.0) than the alternatives used from 1997 to 2009. Post-2009 simulations of WF, WCF, and WCMF applied the same management to those between 1985 and 1997 using average planting and harvest dates for each crop at each site. To ease comparison between rotations, no sorghum was simulated beyond 2009, preferring corn as a better parameterized crop option. The CC strips were changed to continuous winter wheat to represent a rotation with the maximum intensity (i.e., minimum time in summer fallow). While not a realistic management practice, the use of a continuous wheat rotation as the CC treatment meant that predicted estimates of soil C sequestration were the most conservative and susceptible to climate change. All future simulations applied as much fertilizer as demanded by crop growth and therefore removed nutrient limitation on biomass production.

Daily weather input data required to run the future simulations were derived for two RCP scenarios from up to 16 global circulation models (GCMs) that are available from the USGS Geo Data Portal (USGS, 2016). The RCP scenarios inform climate models by making assumptions about global radiative forcing in the year 2100 compared with preindustrial levels; a limit of 4.5 W m^{-2} is assumed by RCP 4.5, with GHG emissions peaking in 2040, whereas global radiative forcing in 2100 is assumed to be 8.5 W m^{-2}, with no limits to GHG emissions. For reference, global radiative forcing in 2016 was 1.985 W m^{-2} (Butler and Montzka, 2017). Site-specific data downloaded (maximum/minimum temperature, maximum/minimum relative humidity, precipitation, eastward wind, northward wind, and downward shortwave solar radiation) were statistically downscaled to 1/24 degree resolution using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou, 2013) and were based on GCMs from the Coupled Model Intercomparison Project phase 5 (CMIP5) that report both RCP 4.5 and RCP 8.5 climate change scenarios. Where a single GCM had considerable gaps (>30 d) in the essential weather input data for a single site, it was not used beyond that time point. Each unique location and rotation treatment was simulated with data for each RCP scenario from each GCM (total n = 3168) from 2009 to 2100. Since the main objective of this study was to generalize the impacts of cropping intensity on SOM dynamics over semiarid regions, the slopes, different entry points to each rotation treatment, and GCMs were used to quantify 95% uncertainty bands for model outputs of interest.

Data Processing and Statistical Analysis

All measured and modeled data were statistically analyzed using R version 3.4.0 (R Core Team, 2017). Measured crop yield data between 1985 and 2009 were checked against the USDA National Agricultural Statistics Service (NASS) yield data (USDA, 2016) reported for nonirrigated cropping in Colorado between 1980 and 2010 (Supplemental Table S4). To annualize both measured and modeled grain and stover yield data by rotation (i.e., cropping intensity), normalized values were calculated on the basis of the average measured yields of each crop within each site within each 12-yr experiment phase. This normalizing was not applied to estimates of C inputs. To compare modeled with measured data, simulated yields were converted from grams of C per square meter to kilograms of biomass per hectare by assuming a C content of 45% for grain and 43% stover of all crops (Latshaw and Miller, 1924; Thomsen and Christensen, 2004). This represented the averages of measured data collected over all crops at all sites between 1985 and 2009, and using higher or lower C content (between 40 and 47%) had no significant impact on our findings.

Since the objectives of this study were to generalize over nonirrigated agroecosystems in a semiarid region, averages were calculated over all sites, slopes, and strips. Standard errors were used to estimate uncertainty of measured averages, and the uncertainty of model averages was estimated using 95% confidence intervals around all available data; before 2009, this meant sites, slopes, and strips, and after 2009 the weather data for each GCM was also used to quantify 95% uncertainty bands for each RCP scenario.

Model estimates of the proportion of C inputs retained in the soil were used to calculate the net sequestration efficiency of each cropping intensity treatment between 1985 and 2100. Starting from 1985, the C inputs to the soil of each treatment were cumulated and the change in soil C stock compared with 1985 levels, therefore providing a metric to compare changes in soil C stocks while accounting for differences in C inputs. Estimates of measured and modeled soil C sequestration rates between 1985 and 2015 were calculated using regression analysis applying linear mixed effect models accounting for site as a random effect (lme function within the nlme package; Pinheiro et al., 2017). Sequestration rates could not be calculated for the WF or WCMF treatments between 1985 and 2015 due to the change in rotation over the second 12-yr phase. Model sequestration rates were also calculated using the same procedure for three 30-yr periods (1985–2015, 2015–2045, and 2045–2075). See Supplemental Material for more information about the modeling techniques used and statistical procedures.

Results and Discussion

This study addressed the issue of how to build and maintain soil C stocks in dryland agroecosystems while also maintaining viable yields. Overall, the highest annualized crop yields and C inputs to the soil were measured and modeled in the most intensively cropped treatments (i.e., those with least time in summer fallow). This resulted in higher soil C stocks (0–20 cm) and more net sequestration under both moderate (RCP 4.5) and extreme climate change scenarios (RCP 8.5).

Measured and Modeled Yields and Soil Carbon, 1985–2009

Crop yields normalized for cropping intensity showed that the treatments with least time in nonvegetated fallow had the highest annualized grain and stover yields (Table 1). While summer fallow is still commonly used across the region (Hansen et al., 2012), our experimental data agree with recent literature indicating that annualized grain yields can be highest in more diverse and intense crop rotations (Peterson et al., 1998; Schlegel et al. 2017). Furthermore, replacing fallow with forage crops can improve PUE and profitability (Nielsen et al., 2017). The trends in crop yields were consistent with changes in SOC (Fig. 1). The more intensively cropped rotations also reported the highest soil C gains.

Overall, measured and modeled values of yields (RMSE = 1689 kg ha^{-1}) and SOC (RMSE = 4.40 t C ha^{-1}) were well matched across the range of treatments within sites with varying topography and soil texture (Table 1; Fig. 1a). Similarly, measured and modeled crop yields were similar to Colorado-wide averages reported by NASS from 1985 to 2009 (Supplemental Table S4; USDA, 2016). Slight discrepancies included the model typically overestimating millet yields (up to 20%) at the high ET site (Walsh) and the model's inability to maintain high

Table 1. Average measured and modeled annualized grain and stover yields ± 1 SE normalized for crop type within each site and rotation phase between 1985 and 2009.

		WF†	WCF	WCMF†	WCM†	WWCM†	CC
		kg dry biomass ha^{-1}					
Grain	Measured	1100 ± 40 *n = 36*	1410 ± 40 *n = 108*	1750 ± 50 *n = 72*	1910 ± 100 *n = 36*	1730 ± 60 *n = 72*	2130 ± 90 *n = 36*
	Modeled	1230 ± 50 *n = 18*	1480 ± 30 *n = 54*	1940 ± 50 *n = 36*	1940 ± 70 *n = 18*	1860 ± 60 *n = 36*	1680 ± 60 *n = 18*
Stover	Measured	1540 ± 60 *n = 36*	1860 ± 60 *n = 108*	2410 ± 70 *n = 72*	2450 ± 150 *n = 36*	2250 ± 80 *n = 72*	2710 ± 160 *n = 36*
	Modeled	1550 ± 50 *n = 18*	1870 ± 40 *n = 54*	2440 ± 40 *n = 36*	2710 ± 70 *n = 18*	2490 ± 50 *n = 36*	2840 ± 130 *n = 18*

† Cropping intensity treatments (0.5 = 1 year of fallow in every 2, 1.0 = no fallow years): 0.5 (wheat–fallow [WF]), 0.66 (wheat–corn–fallow [WCF]), 0.75 (wheat–corn–millet–fallow [WCMF]), and 1.0 (wheat–corn–millet [WCM]; wheat–wheat–corn–millet [WWCM]; continuous [nonmonoculture] cropping [CC]). WF and WCMF treatments were only present in the first rotation phase (1985–1997); WCM and WWCM treatments were only present in the second rotation phase (1997–2009).

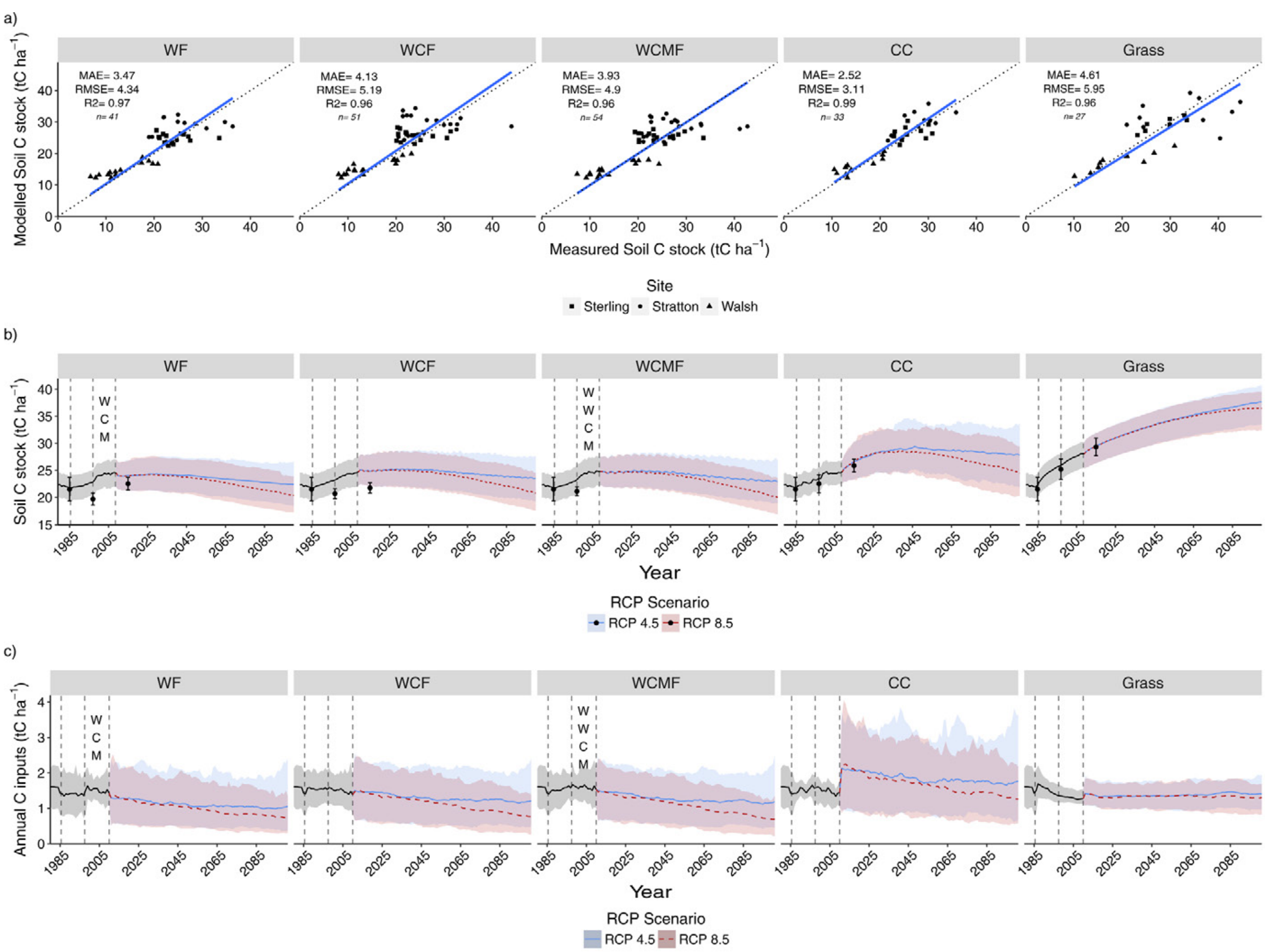

Fig. 1. Soil carbon stock model validation against (a) measured data and (b and c) simulated carbon dynamics for four treatments of increasing cropping intensity (wheat–fallow [WF], 0.5; wheat–corn–fallow [WCF], 0.66; wheat–corn–millet–fallow [WCMF], 0.75; continuous [nonmonoculture] cropping [CC], 1.0) and grassland across a semiarid region of Colorado. (a) Loess-regression with 0 intercept comparing measured and modeled topsoil (0–20 cm) C stocks (t C ha^{-1}) averaged over three slope positions at each of three sites, collected in 1986, 1997, and 2015. WCMF does not include 2015 data. 1:1 dotted black line shown in addition to mean absolute error (MAE), absolute RMSE in t C ha^{-1}, as well as the coefficient of determination (R2), and number of observations (*n*) given for each treatment. (b) Changes in measured (points ± 1 SE) and modeled (lines ± 95% CI) average topsoil (0–20 cm) C stocks (t C ha^{-1}). (c) Changes in modeled total annual C inputs ± 95% CI (t C ha^{-1} yr^{-1}) between 1980 and 2100. From 2010 to 2100, weather inputs from two climate change scenarios (RCP 4.5, solid blue; RCP 8.5, dashed red) are simulated by using up to 16 global circulation models. WF and WCMF treatments were changed to wheat–corn–millet (WCM) and wheat–wheat–corn–millet (WWCM) between 1997 and 2009, respectively (shown by dashed vertical lines).

grain yields in the CC treatment, despite slightly overpredicting stover yields (Table 1).

Model predictions of SOC dynamics after conversion to NT practices in 1985 suggested increased topsoil (0–20 cm) C stocks in all treatments, while measurements showed consistent gains in only the CC and grass treatments (Fig. 1b). This is likely due to processes not simulated by the model, such as residues being transported off site by heavy rainstorms or high winds that can be particularly influential in dryland agriculture (Miner et al., 2013; Plaza-Bonilla et al., 2015). Furthermore, current model parameterization still reflects an older consensus that NT practices will quickly accumulate C in surface soils. The changes made to the model's CLTEFF parameters by our methods (see Supplemental Material) begin to address this limitation, but further studies are required to accurately parameterize the many mechanisms that influence both C incorporation and decomposition rates, beyond those caused by tillage.

Between 1985 and 2015, the model predicted a higher sequestration rate for the WCF treatment compared with measurements where the rate of change was not different from 0 kg C ha^{-1} yr^{-1} (Table 2). Measured results show that topsoil (0–20 cm) C sequestration rates of the CC treatment were not different than those of the grass treatment. This suggests that continuously cropped rotations can have a similar C sequestration potential to that of native grassland, at least in the top 20 cm. While the change from conventional tillage to NT practices may confound changes due to increased cropping intensity, a global analysis by West and Post (2002) suggested that most impact of tillage on C sequestration rates is seen within the first 10 yr after conversion. In our study, these rates appeared mostly linear for the full 30 yr and differed by cropping intensity. Furthermore, our overall rates agree with the global average of West and Post (2002), where an increase in cropping intensity was shown to increase soil C stocks in topsoils (0–22 cm) by 150 ± 110 kg C ha^{-1} yr^{-1}.

Climate Change Impacts on Dryland Agricultural Rotations, 2009–2100

All GCMs predicted an increase in average annual temperatures, suggesting anywhere between a 1 and 8°C rise by the end of the 21st century, depending on the site and climate change scenario (Supplemental Fig. S2). In general, the RCP 8.5 scenario had higher average air temperatures than RCP 4.5; however, most of this difference was realized after 2050. In 2050, the regional average air temperature of simulations under RCP 8.5 was only 0.4°C higher than under RCP 4.5 (13.5 and 13.9°C), but by 2100 the difference had increased to 3.2°C (14.0°C for RCP 4.5 and 17.2°C and RCP 8.5). For reference, the average regional air temperature in 2010 was 11.8°C. Variation in annual precipitation between GCMs was large (Supplemental Fig. S2), but on average predictions suggested a small increase compared with historic amounts at all sites and regardless of RCP scenario.

Overall, the forecasted changes to climate had a detrimental impact on both yields and soil C over the 21st century. While grassland appeared most resilient to changes in temperature and precipitation, all cropped rotations saw limited soil C accumulation and only the continuously cropped (CC) treatment was predicted to have more SOC (0–20 cm) in 2100 than in 2010, and only for the RCP 4.5 scenario (Fig. 1b). The RCP 4.5 scenario consistently reported higher soil C stocks than RCP 8.5; however, the differences were very small for grassland.

Crop Productivity and Soil Carbon Inputs under Climate Change

Corn, wheat, and millet all saw a decrease in yields relative to the average grain and stover measurements taken before 2009 (Supplemental Table S5). Total aboveground wheat yields declined to approximately 37% lower under RCP 4.5 and 50% lower under RCP 8.5 in 2100 than measured yields between 1985 and 2009 (Supplemental Fig. S3). Although our simulations did not account for any potential CO_2 "fertilization" effects, the predicted yield decline is comparable to those reported by Asseng et al. (2013) and Challinor et al. (2014). As a C_3 crop, wheat is likely to be susceptible to the increased drought stress caused by the higher ET rates predicted by climate change. However, in a nonirrigated dryland cropping system, the changes in stomatal conductivity associated with the increased atmospheric CO_2 concentrations may help reduce drought stress and even increase PUE (Fischer et al., 1998; Yang et al., 2016). Similarly, recent developments in understanding breeding strategies and genetic engineering that can provide drought tolerant crop cultivars (Yang et al., 2010, Rauf et al., 2016) is beginning to show promise in helping producers adapt to climate change and improve yields (Thierfelder et al., 2016). These cultivars may also be designed around producing increased root biomass to access available soil water, adding the potential co-benefit of increased C inputs to soil (e.g., Advanced Research Projects Agency-Energy, 2016).

Table 2. Average topsoil (0–20 cm) C sequestration rates ± 1 SE for four cropping treatments and one grassland over three 30-yr periods, calculated using mixed-model linear regressions with site as a random factor. Positive rates are in bold type. Measured regressions use data from three time points (1985, 1997, and 2015) and modeled regressions use annual time points.

Treatment	1985–2015		2015–2045		2045–2075	
	Measured	Modeled	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
	kg C ha^{-1} yr^{-1}					
WF	–†		0 ± 2 NS	–12 ± 2.4 ***	–34 ± 3 ***	–59 ± 3 ***
WCF	**37 ± 46** d NS‡	**105 ± 4** c ***	**6 ± 2** **	–6 ± 2.1 **	–32 ± 2 ***	–62 ± 2 ***
WCMF	–†		0 ± 2 NS	–12 ± 1.8 ***	–35 ± 2 ***	–69 ± 2 ***
CC	**159 ± 49** ab ***	**155 ± 6** b ***	**78 ± 4** ***	**48 ± 4.4** ***	–25 ± 5 ***	–63 ± 5 ***
Grass	**251 ± 67** a ***	**208 ± 7** a ***	**128 ± 4** ***	**127 ± 4.2** ***	**85 ± 4** ***	**76 ± 4** ***

** Significance of difference to a rate of 0 kg C ha^{-1} yr^{-1} at the 0.01 probability level.

*** Significance of difference to a rate of 0 kg C ha^{-1} yr^{-1} at the 0.001 probability level.

† Rates could not be calculated for WF and WCMF before 2015 due to treatments changed to WCM and WWCM between 1998 and 2009.

‡ Letters signify where treatments are significantly different to one another (1985–2015 only); $p < 0.01$.

While corn and millet, both C_4 crops, are also predicted to see losses by 2100, the worst of these are only seen under the RCP 8.5 scenario (Supplemental Table S5; Supplemental Fig. S3). For example, average corn grain yields between 2082 and 2093 are estimated to be 2550 or 1650 kg ha^{-1} under RCP 4.5 or RCP 8.5, respectively (11 and 43% reductions compared with average grain yields measured between 1985 and 2009). The use of a single set of parameter values for millet over the whole region likely meant underestimated yields, particularly under the RCP 8.5 scenario. That said, issues with millet yields and C inputs affect only the WCMF treatment after 2009, and also only 1 in every 4 yr. Model sensitivity analysis results indicate that changes in aboveground productivity are mostly due to changes in temperature, particularly for wheat cropping at locations with a high initial ET (Supplemental Fig. S4). This explains the large differences between yields under RCP 4.5 and RCP 8.5 as the two climate change scenarios mainly differ in the extent of temperature rise after 2050 (Supplemental Fig. S2 and S3). A similar study in the same region predicted similar declines in wheat and corn yields under climate change, with temperature predicted to be the biggest driver of losses but with increased atmospheric CO_2 concentrations offsetting some of the decline (Ko et al., 2012). This may have particular relevance when comparing RCP 4.5 with RCP 8.5 as emissions peak in 2040 in the former and have no limit in the latter.

The tipping point around 2050 was also noted in changes to soil C inputs, paralleling the changes in yield for the different crops (Fig. 1c). An exception to this was C inputs under grassland where the RCP 8.5 scenario resulted in no discernible change and the RCP 4.5 scenario actually increased annual inputs by 0.07 t C ha^{-1}. This is likely due to continuous growth and favorable root/shoot ratios, providing more opportunity for the grass treatment to input C to the topsoil. Few studies examine just the topsoil of nonirrigated dryland regions specifically, but the estimates of C inputs to a nonirrigated WF system by Kong et al. (2005) are in line with our own (~1 t C ha^{-1} yr^{-1}). Put in the context of the different treatments, annual C inputs from both aboveground and belowground sources were highest for those with the highest cropping intensity. The CC treatment added ~2.1 t C ha^{-1} yr^{-1} at the beginning of the future simulations and between 1.7 (RCP 4.5) and 1.4 t C ha^{-1} yr^{-1} (RCP 8.5) at the end of the century. By contrast, inputs to the WF treatment on average decreased from 1.3 t C ha^{-1} yr^{-1} in 2010 to 1.0 (RCP 4.5) or 0.8 t C ha^{-1} yr^{-1} (RCP 8.5) by 2100 (Fig. 1c). While the differences in average annual C input were relatively small, the full range between best- and worst-case scenarios given the different simulated soil and climatic conditions showed considerable variation by 2100, especially for the CC treatment (Fig. 1c). Cumulative C inputs from 1985 to 2100 were predicted to be anywhere between 67 and 335 t C ha^{-1} (Supplemental Table S6). This variability was mainly caused by the difference between the climate predictions as the model is sensitive to temperature and precipitation patterns influencing how much ET occurs in fallow periods and therefore how much water is available for crop growth.

Decomposition and Soil Carbon Outputs under Climate Change

Reduced C inputs under climate change are compounded by an increase in SOM decomposition under higher temperatures. In the DayCent model, the influence of temperature and moisture on decomposition is summarized by the DEFAC parameter. Throughout all simulations, there was a general correlation between a high DEFAC value (i.e., climate conditions increasing decomposition) and SOM losses. Over the first half of the century, those treatments with fallow years (WF, WCF, and WCMF) saw the greatest increase in decomposition, but by 2100 the DEFAC value had risen by up to 60% for all cropped treatments. Climate impacts on the DEFAC value under grassland remained unchanged between 2010 and 2100; this was reflected in model estimates of heterotrophic soil CO_2 emissions. The model sensitivity analysis indicated that under grassland rotations, ~80% of the variability in soil CO_2 emissions were due to changes in precipitation and not temperature (Supplemental Fig. S4). Although total precipitation was forecast to increase under both RCP 4.5 and RCP 8.5 at all sites, the changes in temperature were much more extreme (Supplemental Fig. S2), therefore explaining limited changes in decomposition below grassland. Conversely, the sensitivity analysis indicated that heterotrophic soil CO_2 emissions under cropped rotations were affected more by temperature than by precipitation. This was particularly true for low-intensity rotations (i.e., WF and WCF) at Walsh where initial ET was highest (Supplemental Fig. S4). As a result, heterotrophic soil CO_2 emissions from the cropped treatments increased steadily relative to C inputs between 2010 and 2100, especially for low-intensity rotations under RCP 8.5.

Our results agree with other studies that examine changes in soil C stocks as they respond to climate change, despite some potential methodological limitations (Meersmans et al., 2016; Wiesmeier et al., 2016). While our study focused on topsoil C stocks, recent evidence suggests that potential C losses in topsoil may be somewhat offset by gains in deeper soil layers (Muñoz-Rojas et al., 2017). This study does not account for deeper layers, but we assume that changes to soil C below 20 cm are similar in relative magnitude for all cropped treatments and therefore that the changes in topsoil C are still informative. Furthermore, we did not account for C losses resulting from erosion, which can be high for dryland regions (Nordstrom and Hotta, 2004; Delgado et al., 2013) and can offset C sequestration of the whole soil profile by up to 400 kg C ha^{-1} yr^{-1} depending on initial SOC (Lugato et al., 2016). The model also does not represent more recent understandings of mechanisms that drive soil C dynamics and C stabilization. A more mechanistic model structure is needed to reliably simulate how decomposition of individual C fractions will respond to climate change, given that certain C compounds and their bonds with mineral surfaces can vary in sensitivity to changes in temperature and crop management (Plaza-Bonilla et al., 2014; Bradford et al., 2016).

Sequestration Rates and Soil Carbon Retention under Climate Change

The temporal shifts of crop productivity and decomposition in response to climate change represent the major processes that balance C inputs and outputs to the soil. This results in different amounts of C retained by the different crop rotations. Due to high C inputs and low decomposition rates between 1985 and 1997 (relative to those after 2050), C retention rates started high and then were predicted to diminish as time passed (Supplemental Fig. S5). Until 2050, it was predicted that the greater the C inputs, the greater the change in soil C stocks, but after 2050 even when there were high C inputs sustained over a 12-yr period, there were little or no changes in soil C stocks, regardless of treatment or RCP scenario (Fig. 2; http://bit.ly/AgSoilC). The exception to this was the grass treatment that continued to sequester soil C until 2100 with the same or more C input through plant biomass and often half the heterotrophic soil CO_2 emissions of the cropped treatments (Fig. 1, Fig. 2). The method of calculating sequestration efficiency of the different treatments allowed a comparison of changes in soil C stocks after accounting for differences in C inputs (Supplemental Fig. S5). This idea is similar to that of the additions required to maintain soil C levels and draws similar conclusions for similar system changes (Wilhelm et al., 2004; Kong et al., 2005; Wang et al., 2016).

Our results suggest that regardless of crop intensity, a large proportion of C retained in these dryland soils occurs before 2050 (Fig. 1b). After this point, net C outputs are greater than net inputs and topsoil (0–20 cm) C stocks decline. While many different management strategies may avoid this and help producers adapt to climate change impacts (e.g., cover-cropping, better PUE, drought-resistant crop varieties, better residue management (Plaza-Bonilla et al., 2015), increasing crop diversity and reducing the time in fallow maintained without growing vegetation can help increase SOM immediately, making the soil more resilient to climate change impacts (e.g., by improving water holding capacity) before they become more severe in the latter half of the 21st century (Altieri et al., 2015; Altieri and Nicholls, 2017). However, it is also important consider that impacts of SOM on soil available water are also related to texture (Minasny and Mcbratney, 2017). The complex feedbacks between SOM and crop production are greatly simplified by the DayCent model, and therefore it is possible that the predicted SOM gains realized by 2050 increase nutrient and water retention, stimulating further crop production and more SOC sequestration. However, the inverse is also possible, and SOM may be more sensitive to climatic change than the model suggests. These are fundamental limitations of using any ecosystem model (including DayCent) to simplify complex mechanisms and should be assessed alongside other sources of uncertainty.

Policy Considerations to Increase Soil Organic Matter in Dryland Agriculture under Climate Change

When conservation agriculture practices are widely adopted, many of the impacts are public benefits (e.g., reduced CO_2 emissions and conserved soil biodiversity), but most of the costs are internalized by producers (Knowler and Bradshaw, 2007). Therefore, to successfully encourage these conservation agriculture practices, policy must help to address and mitigate these costs. In drylands, a large private cost of conservation agriculture can be the opportunity cost of not using the crop residues for livestock fodder or as a bioenergy feedstock (Miner et al., 2013; Plaza-Bonilla et al., 2015). Developing C markets that include sequestration in soils has the potential to help offset these costs (Pautsch et al., 2001), but implementation has proven to be difficult and inefficient (Antle and Diagana, 2003; Simone et al., 2017). Public policy to facilitate a transition toward increased cropping intensity/diversity specifically appears to be more realistic, but implementation began only recently worldwide (Joshi et al., 2004; Alauddin and Quiggin, 2008; Binswanger-Mkhize and Savastano, 2017). Global trends suggest that dryland producers

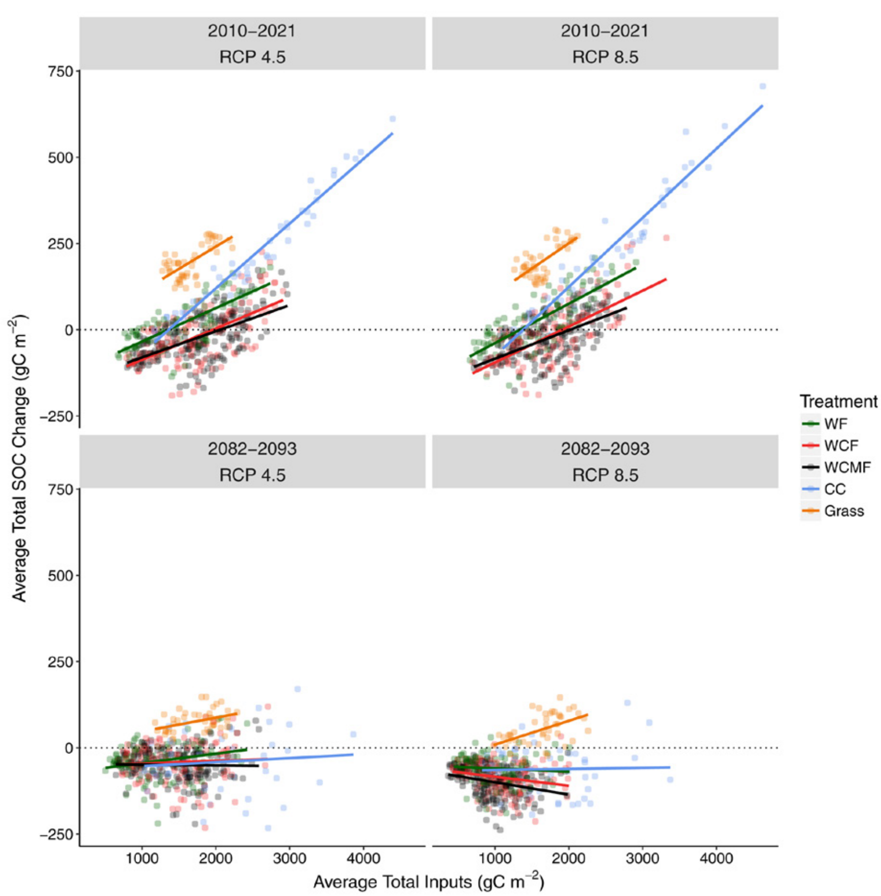

Fig. 2. Relationship between the C inputs (g C m^{-2}) averaged over two 12-yr phases (2010–2022, upper panels; 2082–2093, lower panels), and the change in soil C stocks (g C m^{-2}, 0–20 cm) over the same 12-yr phases. The points of four treatments of increasing cropping intensity and one grassland treatment are plotted by color (wheat–fallow [WF], green; wheat–corn–fallow [WC], red; wheat–corn–millet–fallow [WCMF], black; continuous [nonmonoculture] cropping [CC], blue; grass, orange), along with a linear regression estimated over all available points. Plotted data points simulated by DayCent for two climate change scenarios (RCP 4.5, left panels; RCP 8.5, right panels) include three sites, multiple rotation entry points, and up to 16 global circulation model inputs (see Fig. 1 caption for more detail). See moving GIF at http://bit.ly/AgSoilC for sequence of all 12-yr phases between 2010 and 2100. SOC, soil organic C.

are beginning to move toward increased cropping intensity and diversity as studies indicate these systems can maintain high annualized yields and be more resilient to various impacts of climate change (Smith and Young, 2000; Holt-Giménez, 2002; Olesen et al., 2011; Challinor et al., 2014; Karimi et al., 2017). Furthermore, producers are beginning to recognize that increasing crop diversity can reduce the risk associated with crop failure. Effective policy measures that improve marketing infrastructure (especially for “minor” crops) and on-farm technology and that change perceptions of risk can take advantage of these trends, ultimately increasing SOM through more soil C inputs (Maaz et al., 2017). The move away from traditional WF systems has already begun (Hansen et al., 2012; Maaz et al., 2017), but our results suggest that a gradual increase in intensification is less beneficial than adopting continuous cropping directly, both regarding yields and SOC under climate change (Table 1; Fig. 1).

Conclusion

Our objective was to evaluate how dryland agricultural management in semiarid climates could build and maintain SOM while also maintaining yields under current and future climates. More intensively cropped rotations have the greatest potential for annualized yields as well as the highest soil C sequestration rates. This is advantageous to producers and has the added benefits of helping mitigate climate change and improve soil quality. With climate change impacts likely to increase drought frequency over the coming century, management systems need to be both resilient and flexible given unpredictable conditions. Studies such as ours provide the scientific basis for implementing such management practices, ultimately informing effective agricultural policy. Incentivizing cropping intensification in dryland systems can provide win-win outcomes that maintain yields and mitigate the CO_2 emissions associated with agriculture.

Acknowledgments

The authors thank Kevin Larson and J.R. Herman for their help with the long-term plot management, Mike Whitfield for helpful code for the sensitivity analysis, and Steve Del Grosso for useful discussion on simulating the three long-term experimental sites. Funding for this work was provided by USDA-ARS Cooperative Agreement 58-5402-4-016.

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