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Optimizing multifunctional agroecosystems in irrigated dryland agriculture to restore soil carbon – Experiments and modelling

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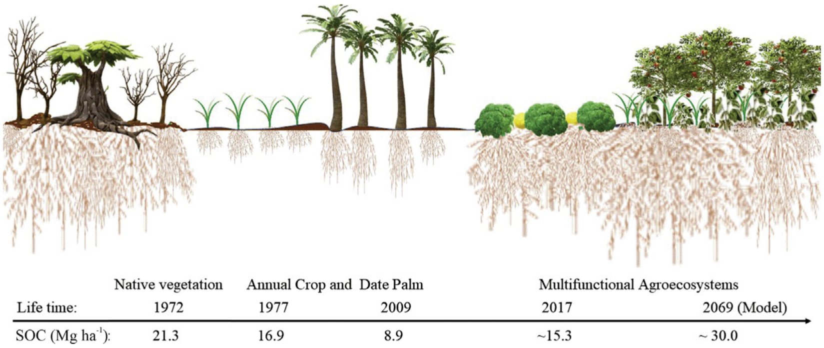
HIGHLIGHTS

- Crop/cover crop residues of >5 Mg C ha^{-1} year^{-1} increase SOC by >0.5 Mg C ha^{-1} year^{-1}.
- Replacing conventional with no tillage enhances C accumulation by factor 8 to 3.
- For correct simulation of the soil water balance RothC must use a daily timestep.
- SOC stocks similar to the original dryland forest could be reached in 20 to 27 years.

GRAPHICAL ABSTRACT



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ABSTRACT

Irrigated dryland agroecosystems could become more sustainable if crop and soil management enhanced soil organic carbon (SOC). We hypothesized that combining high inputs from cover crops with no-tillage will increase long-term SOC stocks. Caatinga shrublands had been cleared in 1972 for arable crops and palm plantations before implementing field experiments on Mango and Melon systems (established in 2009 and 2012, respectively). Each of the two experiments were managed with no-till (NT) or conventional till (CT), and three types of cover cropping, either a plant mixture of 75% (PM1) or 25% (PM2) legumes, or spontaneous vegetation (SV). The RothC model was used with a daily timestep to simulate the soil moisture dynamics and C turnover for this dry climate. Carbon inputs were between 2.62 and 5.82 Mg C ha^{-1} year^{-1} and increased the depleted SOC stocks by 0.08 to 0.56 Mg C ha^{-1} year^{-1}. Scenarios of continuous biomass inputs of ca. 5 Mg C ha^{-1} year^{-1} for 60 years are likely to increase SOC stocks in the mango NT beyond the original Caatinga SOC by between 19.2 and 20.5 Mg C ha^{-1}. Under CT similar inputs would increase SOC stocks only marginally above depletion (2.75 to 2.47 Mg C ha^{-1}). Under melon, annual carbon inputs are slightly greater (up to 5.5 Mg C ha^{-1} year^{-1}) and SOC stocks would increase on average by another 8% to 22.3 to 20.6 Mg C ha^{-1} under NT and by 8 Mg C ha^{-1} under CT. These long-term simulations show that combining NT with high quality cover crops (PM1, PM2)

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would exceed SOC stocks of the initial Caatinga within 20 and 25 years under irrigated melon and mango cultivation, respectively. These results present a solution to reverse prior loss of SOC by replacing CT dryland agriculture with irrigated NT plus high input cover crops agroecosystems.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has highlighted the need for carbon sequestration to avoid a rise in global temperature of >1.5 °C (Masson-Delmotte et al., 2018). The United Nations have adopted the 2030 Agenda for Sustainable Development (UNGA, 2015) and the first two of the 17 Sustainable Development Goals (SDGs) are to end poverty and hunger, and in particular, SDG 13, Climate Action. Agriculture needs to embrace its important roles in both climate regulation and food production. The integration of agricultural management with land use and climate change objectives (Lorenz et al., 2019) will help to regulate the carbon (C) cycle, increasing sequestration C into the soil. The soil organic carbon (SOC) is estimated to be three times larger than the atmospheric carbon pool (Lal, 2004). Improving SOC through agricultural management secures terrestrial ecosystem functions and food production, affecting directly or indirectly more than half of all SDGs (Jónsson et al., 2016).

This is particularly important for dryland areas, which cover over 40% of the global land surface, inhabited by nearly 38% of the world population (Cherlet et al., 2018; Huang et al., 2017). The Brazilian semi-arid covers 1 million km^2 and is inhabited by 28 million people. This region has 1.6 million agricultural holdings, 95% being smallholders (IBGE, 2012). To support its population and develop the region, public policies intend to change rainfed subsistence agriculture into intensive irrigated agriculture (IIA) with annual and perennial crops (Araujo Filho, 2013). IIA extends over 1.2 million ha (ANA, 2017) usually as monocultures with high use of external inputs. However, the intensive use of soil tillage, synthetic fertilizers, and irrigation have caused substantial SOC reduction, soil salinization, and increased water scarcity, all of which accelerate climate change (Müller Carneiro et al., 2019; Smith et al., 2015).

The use of plant mixtures for cover cropping and tillage systems (conventional, no-till) are components of the new strategy for agriculture in the semiarid areas to improve SOC storage (Giongo et al., 2016). This will affect other ecosystem services (Santos et al., 2018) and, eventually, promote food security. In addition to advancing productivity in IIA, models of sustainable soil management need to be developed to increase and stabilize the SOC. There are many models available to simulate SOC dynamics, e.g. RothC (Coleman and Jenkinson, 1996), Century (Parton et al., 1987), DNDC (Li, 1996) or SOMM (Chertov et al., 1997). Among these models, RothC is one of the most frequently used to simulate SOC content in the soil surface layer due to the simplicity and availability of input data (Coleman et al., 1997; Herbst et al., 2018; Liu et al., 2009; Taniyama et al., 2004).

We hypothesized that change of tillage and use of plant mixtures as cover crops will improve SOC stock in dryland irrigated agriculture. Eventually, this could even exceed the equilibrium SOC found under natural dryland forest depending on soil disturbance, extent of soil cover and plant diversity, determining net biomass C input of the respective agroecosystem. To test these hypotheses, the model was initially calibrated to reach equilibrium SOC for the Caatinga. We then used the C inputs and SOC data from historic land use change and two long-term field experiments to calibrate the RothC model against data from soils under melon and mango cropping. These experiments compared different multifunctional agroecosystems in terms of SOC management using annual and perennial crops and different cover crops and tillage intensities. Once calibrated, we used the model to predict the long-term future impact of these management systems on SOC dynamic in irrigated dryland agriculture.

2. Materials and methods

2.1. Dataset used

We selected datasets collected for two multi-factorial long-term experiments (1) a mango orchard (*Mangifera indica* L., cv. Kent) system (Mango) and (2) melon crop (*Cucumis melo*, L.) system (Melon), at Embrapa Semi-Arid (Brazilian Agriculture Research Corporation), in Petrolina, PE (Fig. 1).

The Mango and Melon experiments started in 2009 and 2011, respectively. The area, originally under native tropical dry shrublands (hyperxerophilic Caatinga vegetation), was converted into arable agriculture in 1972. For 16 years it was cultivated with corn (*Zea mays* L.), common bean (*Phaseolus vulgaris* L.) and watermelon (*Citrullus lanatus* L.), using conventional tillage. In 1988, a date palm plantation (*Phoenix dactylifera* L.) followed for 20 years. Before the Melon experiment there were two more years of fallow and common bean. Details of the site, soils and experiments are given in Table 1.

2.2. Climate data

The climate of the region is BSwh' (semiarid) according to the Köppen classification; the average annual precipitation is <500 mm, concentrated in three to five months; monthly average temperatures range from 18.7 to 33.6 °C. The sandy loam soil of the area is classified as Haplic Acrisol (WRB, 2014). Data of mean daily temperature, evaporation, and precipitation were measured at the agrometeorological weather station located on the experimental farm. The irrigation requirement was calculated using the reference evapotranspiration (ETo), estimated by the Penman-Monteith method. For RothC any irrigation water input was added to the precipitation (Fig. 2). Standard crop coefficients (Doorenbos and Pruitt, 1977) were used to estimate the respective actual evapotranspiration (ETc).

2.3. Field experiments and treatments

In both long-term field experiments, the treatments consisted of two soil tillage systems, no-tillage (NT) and conventional tillage (CT), combined with three mixtures of cover crops [75% leguminous species + 25% grass and oilseed species (PM1), 25% leguminous species + 75% grass and oilseed species (PM2) and spontaneous vegetation (SV)]. The experimental designs were split-plot randomised blocks, in four replicates, with soil tillage systems in the plot and mixtures of cover crops in the subplots.

In the Mango experiment, each subplot was composed of three rows, with three mango trees, totaling nine trees per subplot, at 8 × 5 m spacing, with a total area of 360 m^2. The mixtures of cover crops were grown in 6-m-long strips between rows, leaving a free border of 1 m on each side of the mango tree rows. In the Melon experiment, each plot was 10 × 10 m^2 and each block was 600 m^2. The seeds were sown in furrows at a spacing of 0.5 m.

PM1 and PM2 contained 14 species, which included oilseed, grass, and leguminous plants, but at different proportions between the mixtures (Freitas et al., 2019; Giongo et al., 2016; Pereira Filho et al., 2019). The SV control was composed of *Desmodium tortuosum* (Sw.) DC, *Macroptilium lathyroides* (L.) Urb., *Digitaria bicornis* (Lam.) Roem. Schult., *Dactyloctenium aegypitium* (L.) Willd., *Commelina difusa* Burm. f., *Acanthospermum hispidum* DC, *Euphorbia chamaeclada* Ule, *Waltheria*

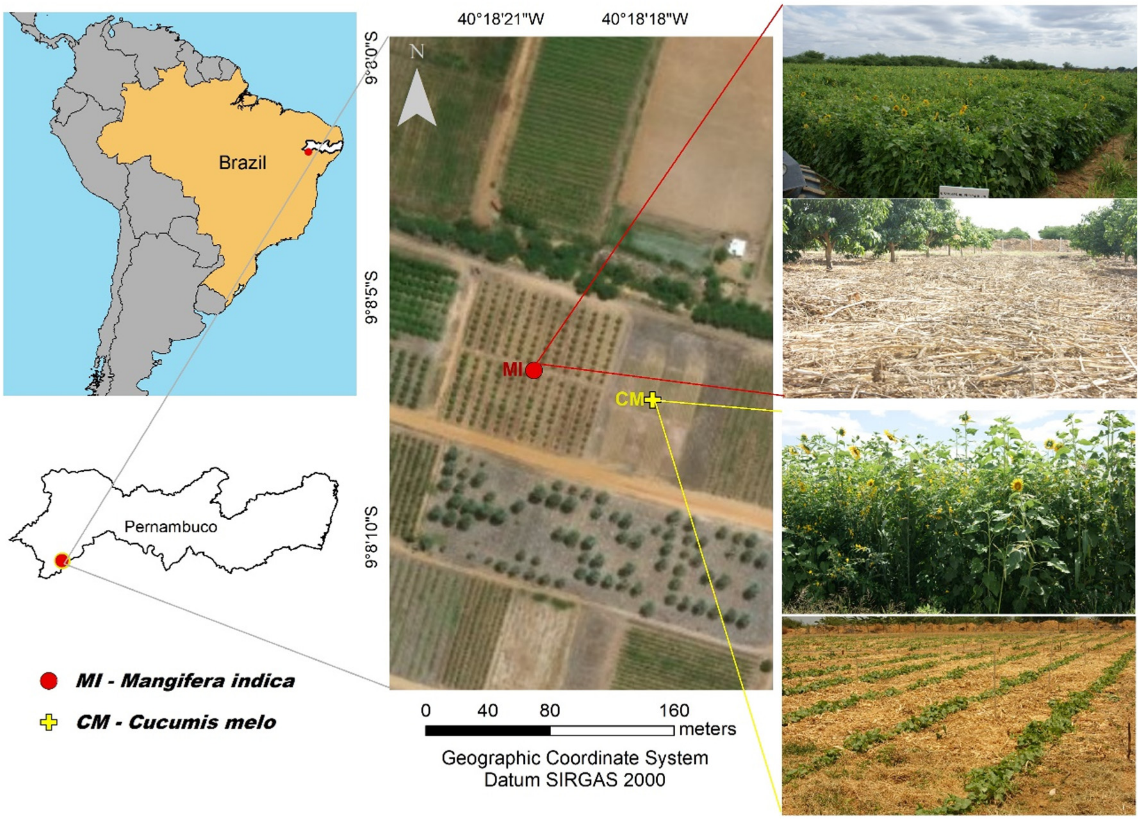

Fig. 1. Location of the study sites in Brazil.

Table 1
Details of the site, soil and experiments.

	(1)	(2)
Sites		
Local	Embrapa Semiarid	Embrapa Semiarid
Geodesic Coordinate System (latitude; longitude) (°)	09°09′S 40°22′W	9° 08′S 40°18′W
Altitude ellipsoid (WGS 84) (m)	366	365,5
Maximum annual temperature (°C)	33.6	33.6
Minimum annual temperature (°C)	18.7	18.7
Mean annual rainfall (mm)	567	567
Soil type	Haplic Acrisol	Haplic Acrisol
Soil		
Depth (m)	0–0.2	0–0.2
Sand (g kg^{-1})	869.79	831.26
Silt (g kg^{-1})	68.83	119.78
Clay (g kg^{-1})	61.63	48.96
Soil texture	Sandy loam	Sandy loam
pH	6.6	6.6
Organic C (g kg^{-1})	6.3	5.8
P (mg dm^3)	34.91	47.34
Bulk density (Mg m^{-3})	1.50	1.45
Experiment		
Previous land use	*Phoenix dactylifera*	Annual crop and fallow
Experiment planted	2009	2012
Experimental design	Randomised complete block	Randomised complete block
Field replication	4	4
Plant	Mango (*Mangifera indica*)	Melon (*Cucumis melo*)
Plots	24	24
Plot size (m^2)	8640	2400
Plant spacing within rows (m)	8 × 5	2 × 0.3
Planting density (plants ha^{-1})	216	4000

rotundifolia Schrank, *Waltheria* sp. L., *Tridax procumbens* L., *Ipomoea mauritiana* Jacq., *Ipomoea bahiensis* Willd. Ex Roem. Schult. and *Amaranthus deflexus* L.

In the NT systems, cover crops were managed using a manual mower at anthesis of most species, ca. 70 days after sowing. Plants were cut at 5 cm above ground, and their shoot biomass was deposited on the soil, in between the mango rows and mixed with melon residues. In the CT systems, the phytomass was incorporated with a disc plow to 20 cm depth, followed by harrowing with a light open-disc harrow.

2.4. Soil carbon and aboveground and belowground inputs

2.4.1. Soil organic carbon

The soil organic matter content in the 0–20 cm layer was measured in 1977 and 1997 by Lopes et al. (1977) and Bassoi et al. (1999a, 1999b). A factor of 1.72 was used to convert organic matter into SOC assuming that organic matter contains 58% of organic carbon (Nelson and Sommers, 1996). SOC was measured in 2009, 2013, 2015 and 2017 for Mango, and in 2009, 2012, 2014 and 2017 for Melon. The SOC stocks were calculated using SOC, soil bulk density data, and depth.

In order to estimate the reference SOC under Caatinga in 1972, a four hectare area of a nearby preserved Caatinga forest was divided into four subsections to take composite soil samples (eight individual samples) for 0–5 cm, 5–10 cm and 10–20 cm depth in each subsection. Similarly, composite samples were taken in each experimental unit of both long-term experiments. The composite samples were transferred in plastic bags to the Laboratory of Soil and Plant Analysis of Embrapa Semiarid, air dried and passed through 2.0 mm sieves to obtain air dry fine earth for analysis. In each experimental unit and the reference area, undisturbed samples were collected in each layer, using a 5 cm × 5 cm volumetric ring to determine the soil bulk density (Donagema et al., 2011). The total C contents were obtained by dry combustion using an elemental analyzer (LECO, model TRUSPEC CN). The total SOC stocks in each

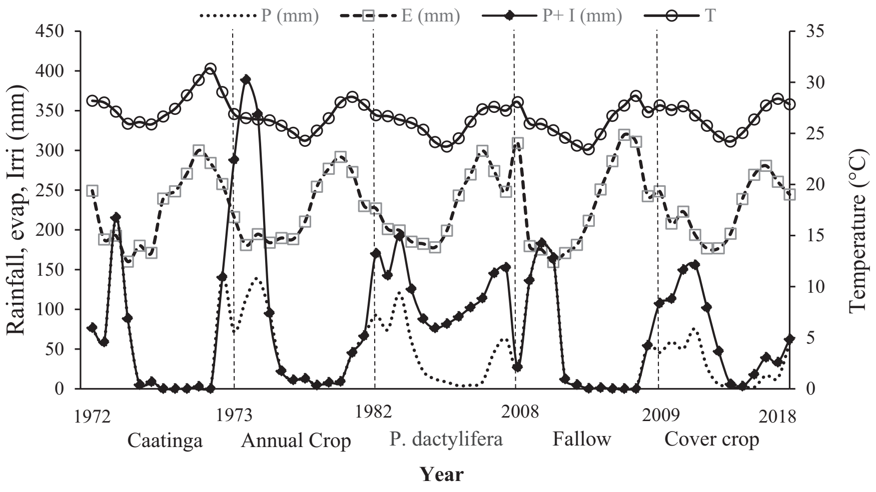

Fig. 2. Monthly average evaporation (E), cumulative rainfall (P), and cumulative rainfall + irrigation (P + I) and mean air temperature (T) (January 1972 to December 2018). Data of the Agrometeorological Station of Embrapa Semi-Arid Agriculture, Petrolina, PE, Brazil.

area were obtained calculating the equivalent soil mass per layer (Ellert et al., 2010).

For the calculation of the equivalent mass, the relative mass of the soil was considered in the different treatments (Eq. (1)).

$$M_{soil} = ds \cdot T \cdot A \quad (1)$$

where M_{soil} = soil mass (Mg ha^{-1}); ds = soil bulk density (Mg m^{-3}); T = thickness (m); and A = area (10,000 m^2).

The measurement under Caatinga was considered as a reference and the thickness (T) was added or subtracted from the respective treatments (Eq. (2)).

$$T_{ad/sub} = (M_{ref} - M_{treat}) \cdot f_{ha}/ds \quad (2)$$

where $T_{ad/sub}$ = soil thickness layer to be added (+) or subtracted (−) (m); M_{ref} = equivalent mass of the soil (Mg ha^{-1}) in the reference area (Caatinga); M_{treat} = soil equivalent mass in each treatment (Mg ha^{-1}); f_{ha} = conversion factor from ha to m^2 (0.00001 ha m^{-2}); and ds = soil bulk density (Mg m^{-3}).

The stocks of C in equivalent mass were calculated (Eq. (3)).

$$SOC_{em} = cc \cdot ds\ (T \pm T_{ad/sub}) \cdot A \cdot F_{kg} \quad (3)$$

where SOC_{em} = stock of total SOC, expressed as equivalent mass in Mg ha^{-1}; cc = content of C, g kg^{-1}; T = soil thickness of the layer, expressed in m; and F_{kg} = conversion factor of kg to Mg (0.001 Mg ha^{-1}). The soil carbon stocks, in the 0–20 cm layer, in each treatment were obtained through the sum of their respective stocks in the evaluated layers.

2.4.2. Aboveground and belowground C inputs

RothC assumes inputs to the soil are from all forms of organic carbon entering the soil i.e. shoots and stubble (C_s), roots (C_r), and root exudates (C_e). The annual carbon input from Caatinga forest was calculated by running RothC in inverse mode to generate the input required to match the initial stock of SOC in 1972. The calculated plant C inputs obtained for the period between 1973 and 2008 for Mango or 2010 for Melon were taken from Lopes et al. (1977) and Bassoi et al. (1999a, 1999b), respectively. From 2008 for Mango and from 2010 for Melon, the aboveground dry matter data for corn, common bean and watermelon were taken from Martins (2010) and Nosoline (2012). Root biomass for those crops was estimated from aboveground dry matter using the method described in Bolinder et al. (2007). For date palm both aboveground and root dry matter was taken from Bassoi et al. (1999a, 1999b). For all crops we assumed that the root exudates are equivalent to 9% of the total aboveground biomass dry matter (Kuzyakov and Domanski, 2000).

For both long-term field experiments, the aboveground and root biomass were determined by collecting three samples of aboveground and five samples of root biomass on each subplot. Samples were dried at 65–70 °C for 72 h to determine dry biomass and C contents. In each treatment, trenches were cut (0.2 m × 0.2 m × 1.0 m) to sample the fine root biomass of the cover crops and melon. To determine root biomass, soil blocks with a volume of 20 cm^3 were removed at depths of 0–0.2 m. These soil samples were sieved and washed through 2 mm sieves to separate the roots from the soil. In the laboratory, the roots were washed again in distilled water and dried at 65–70 °C for 48 h.

To estimative C input from aboveground and belowground biomass we assumed a C content of 45% dry matter. Further details about the long-term field experiments can be found elsewhere (Pereira Filho et al., 2019; Brandao et al., 2017; Freitas et al., 2019; Giongo et al., 2016; Mouco et al., 2015).

2.5. The RothC model

For this study a daily version of the Rothamsted carbon model (RothC) was used, to allow a realistic simulation of soil moisture and SOC dynamics in this dry region. Other than using daily meteorological data no further changes were made to the model. In RothC, SOC is split into four active compartments and a small amount of inert organic matter (IOM). The four active compartments are DPM, RPM, Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition. For more details see Coleman et al. (1997); Gottschalk et al. (2012); Kamoni et al. (2007); Smith et al. (1997).

In this semi-arid region, the standard monthly timestep version of RothC was not able to simulate soil moisture status because monthly evapotranspiration always exceeds the monthly precipitation, even when irrigated. This meant the rate modifying factor in the model for moisture was always the minimum value: 0.2. Because of this SOC increased unrealistically. After irrigation or rainfall, the soil will temporarily be much wetter than these average monthly data would suggest. By using a daily timestep the model was able to correctly simulate the soil moisture status throughout the year, in both rainfed and irrigated experiments and consequently estimate SOC and crop residue decomposition realistically.

2.5.1. Running the model

For both experimental sites the model was run to equilibrium in inverse mode to generate the inputs required to match the SOC stock for Caatinga, using a DPM/RPM ratio of 0.67. This is the default value for Savana plant material, which is similar to Caatinga. The inert organic matter (IOM) of 1.6 Mg ha^{-1} was estimated using Eq. (4) suggested by Falloon et al. (2000).

$$\mathrm{IOM} = 0.049\ \mathrm{SOC}^{1.139} \tag{4}$$

After equilibrium the model was run for 16 years of annual cropping using annual inputs of 0.93 Mg C ha^{-1} year^{1} (Lopes et al., 1977), and for 20 years of date palm with an annual input of 1.20 Mg C ha^{-1} year^{1} (Bassoi et al., 1999a, 1999b). Before starting Mango and Melon experiments a year of bare fallow and two years of fallow plus arable were added to the model, respectively. Daily meteorological data (see Section 2.2) were used. The soil was left bare for 270 (Mango) and 230 (Melon) days in CT treatments for each year during the experiment. The soil was considered to be covered with plants/residues for all of the year in NT treatments. The effect of NT was simulated using the RothC plant cover factor of "1" when the soil was not bare, either due to vegetation and/or biomass residues on the surface.

For the phase before the experiment we used the default DPM/RPM ratio, i.e. 1.44, for residues of annual crops and date palm alike. For the phase of the experiment where green manure was added we used a DPM/RPM ratio of 3.35 (77% DPM and 23% RPM) as suggested by Yao et al. (2017) and Zhang et al. (2019).

To model future SOC stock changes we used the same annual C inputs, and DPM/RPM ratio that were used for the Mango or Melon phase of the experiment. The model was run 50 years into the future, using daily average weather data for Mango and Melon.

2.6. Statistical analysis

Values of the total SOC stocks and total C inputs of aboveground and belowground plant matter from the long-term field experiments were analyzed for normality by Shapiro-Will test ($p > 0.05$). The homoskedasticity was evaluated by Bartlett's method ($p > 0.05$), and data homogeneity according to Lewis (1995). The initial value for Caatinga was ignored in the statistical analysis. Average crop residue input and SOC data according to land use change before and during the Mango and Melon experiments were used to the simulations.

The model performance was evaluated by comparing the simulated values with those measured in each single treatment, and for each site and both sites in order to increase the degrees of freedom and hence the robustness of the analysis. The root mean square error (RMSE), mean difference (MD), model efficiency (EF), and the sample correlation coefficient (r) were calculated using MODEVAL (Smith et al., 1996, 1997). The RMSE is the relative difference between the observed and simulated values, weighted as a percentage of the mean value of observed data. The lowest possible value of RMSE is zero, indicating that there is no difference between simulated and observed data. The MD is the mean difference between observed and simulated data and gives an indication of the bias in the simulation. The MD can be related directly to a value of the *t*-statistic. A *t* value greater than the critical two tailed 2.5% *t* value indicates that the simulation showed a significant bias: either over or underestimation. The EF provides a comparison of the efficiency of the chosen model to the efficiency of describing the data as a mean of the observations. Values of EF range from 1 to negative infinity. Best performance is at EF = 1. Negative values indicate that the average values of all measured values are a better estimator than the model. The correlation coefficient (r) is used to assess whether simulated values follow the same pattern as measured values. Further details can be found in Smith et al. (1996, 1997). The total SOC stock in the Caatinga, which was used to initialise the model in inverse mode, was discarded in the statistical analyses because it is not an independent value.

3. Results

3.1. Effect of land use change on SOC

Soil organic carbon stocks under conventional agriculture in the two long-term experiments decreased from originally 21.3 Mg C ha^{-1} under Caatinga to 16.9 Mg C ha^{-1} under annual cropping, and decreased further under date palm to 8.9 Mg C ha^{-1} in 2009, respectively (Table 2). All treatments improved SOC stocks under Mango and Melon, increasing the overall average SOC stocks in the 0-20 cm soil layer of the NT treatments from 8.9 Mg C ha^{-1} in 2009 to between 11 and 15 Mg C ha^{-1} in 2017. In CT treatments, cover crops were less effective than under NT (Table 2).

Under Mango, the highest SOC stock change occurred in the NT and two plant mixtures (NT-PM1 and NT-PM2) - about 6 Mg C ha^{-1} in eight years. NT-SV was similar to CT-PM1. However, soil tillage affected the SOC stocks across all plant mixtures, with impacts decreasing from legumes to spontaneous vegetation. In both PM treatments, tillage decreased the SOC stocks by 4.5 to 4.8 Mg ha^{-1}. Treatment CT-SV,

Table 2
Measured average annual C inputs and final SOC stocks during the Mango and Melon cover cropping experiments and historic inputs and observed SOC stocks.

Treat[a]	Mango				Melon			
	NT	CT	NT	CT	NT	CT	NT	CT
	C input (Mg C ha^{-1} year^{-1})		SOC stock (Mg C ha^{-1})		C input (Mg C ha^{-1} year^{-1})		SOC stock (Mg C ha^{-1})	
PM1	5.10 ± 0.18	4.90 ± 0.08	15.32 ± 2.17	13.44 ± 1.63	5.52 ± 0.49	5.82 ± 0.11	11.32 ± 1.36	12.86 ± 1.17
PM2	4.82 ± 0.12	4.76 ± 0.14	15.10 ± 2.54	10.58 ± 0.62	5.14 ± 0.40	5.75 ± 0.25	15.31 ± 0.84	14.64 ± 0.57
SV	2.62 ± 0.19	2.55 ± 0.12	11.88 ± 0.98	9.23 ± 0.15	3.74 ± 0.21	3.82 ± 0.28	12.79 ± 0.82	10.77 ± 1.52

Historic	C input (Mg C ha^{-1} year^{-1})	SOC stock (Mg C ha^{-1})
Caatinga equilibrium (1972)	1.24[b]	21.33 ± 1.26
Annual crop (1977)	0.93[c]	16.86[c]
Date palm (1997)	1.20[d]	9.78[d]
CBE (2009)	–	8.90 ± 0.69

PM1–75% legume species + 25% grass/oilseed species, PM2–25% legume species + 75% grass/oilseed species; SV - spontaneous vegetation; CT - conventional; NT - no-till, CBE - characterization before starting the experiments in 2009.

[a] Average followed by the standard error of the mean.

[b] Calculated by running RothC in inverse mode to find the C input in the equilibrium.

[c] Lopes et al. (1977), Martins (2010) and Nosoline (2012).

[d] Bassoi et al. (1999a, 1999b).

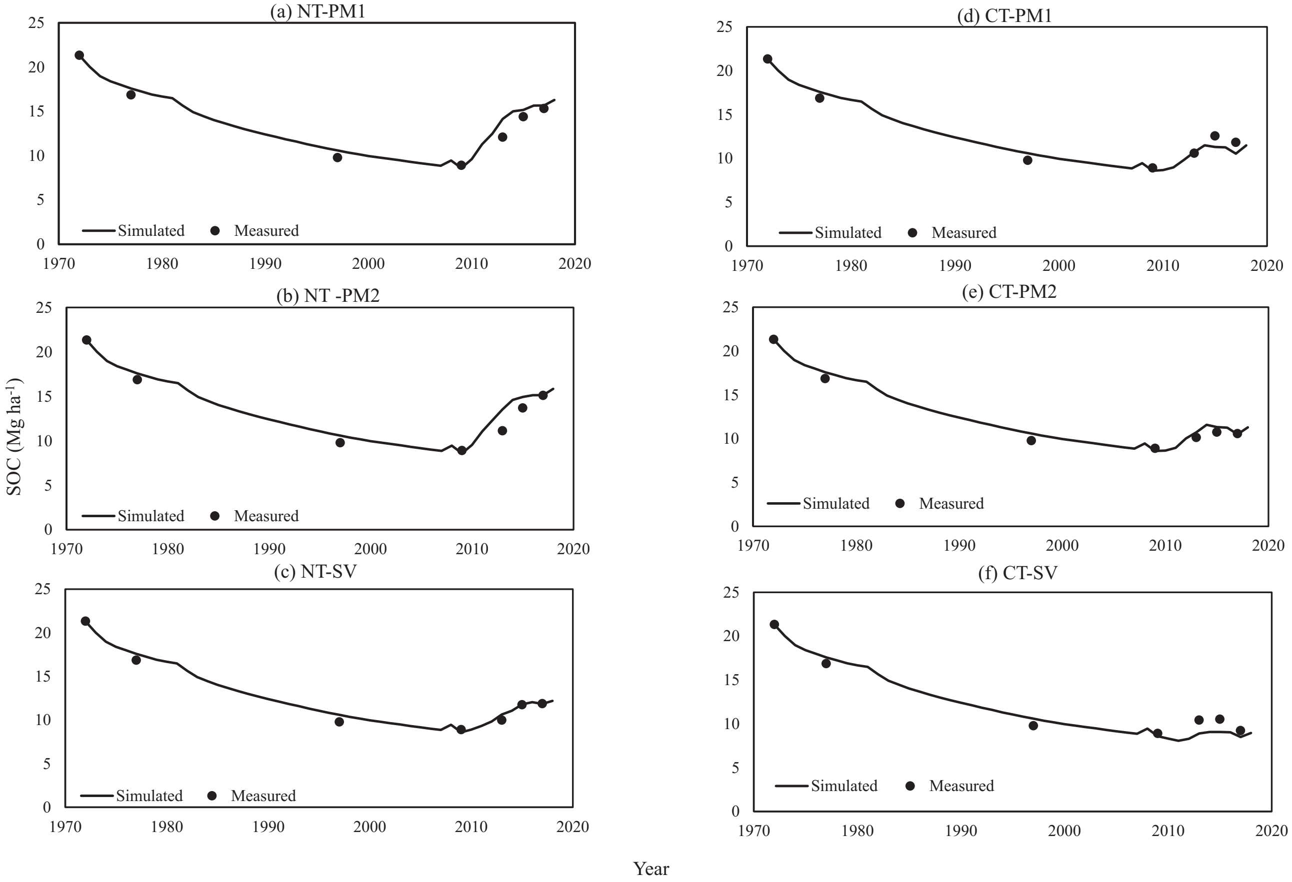

Fig. 3. Modelled (lines) and measured (symbols) SOC in the 0–20 cm layer from the data set of long-term field experiment with Mango in the Brazilian Semiarid, using the RothC model. Legend: PM1–75% legume species + 25% grass/oilseed species, PM2–25% legume species + 75% grass/oilseed species; and SV, spontaneous vegetation, all under conventional (CT) and no-till (NT).

representing the conventional mango production system in the region, had the lowest SOC stock among all treatments (Table 2).

Under Melon, the highest SOC stock increase occurred in PM2, independent of tillage (NT-PM2 and CT-PM2; Table 2). The soil tillage affected SOC stocks only under spontaneous vegetation, when conventional tillage (CT-SV) lowered SOC stocks, similarly to the effect in the Mango system.

For modelling SOC dynamics, it is very important to estimate the annual C inputs to soils. Our results showed for the Mango and Melon, that the highest annual C input was obtained when plant mixtures were introduced. The annual average C inputs into the agroecosystems with plant mixtures were 4.89 and 5.56 Mg C ha^{-1} $year^{-1}$ to Mango and Melon, respectively. In contrast, C inputs from spontaneous vegetation (average from NT and CT) were only 2.59 and 3.78 Mg C ha^{-1} $year^{-1}$ for Mango and Melon, respectively. The respective higher annual C inputs to the Melon system were due to the additional inputs from above- and belowground crop residues. Therefore, the final SOC enrichment was greater in the Melon than in the Mango system; the latter, however, did not account for the accumulated woody biomass of the Mango trees.

Greater levels of SOC enrichment were found for all combinations of high quality cover crops with main crops under reduced tillage but tilling the soil eliminated this effect.

3.2. Model performance

The performance of the RothC model was tested by comparing modelled versus observed SOC from these datasets including two long-term field experiments. SOC change was modelled and evaluated using different organic C inputs from different agricultural plants, cover crop mixtures and tillage intensities. First, before the field experiments were initiated, the Roth C model estimated the inputs from native vegetation to match initial equilibrium SOC stocks of Caatinga in 1972 and land use change to conventional agriculture (Fig. 3). The simulated loss of SOC under arable cultivation (CT) for a total of 18 years and date palm for another 20 years was 12.71 Mg C ha^{-1} (20 cm soil profile), compared to the measured loss of 12.43 Mg C ha^{-1}. The overall difference between measured and simulated SOC was 0.28 Mg C ha^{-1} only (2%).

The RothC model was able to predict SOC stock increases in the same proportions as observed, in both field experiments. For Mango, under NT-PM1, for example, the final SOC stock measured in 2017 was 15.3 Mg ha^{-1}, compared to the model estimate of 15.7 Mg C ha^{-1}. In the CT-SV, the measured and estimated SOC values were 9.2 and 8.5 Mg C ha^{-1}, respectively (Fig. 3). Under Melon (Fig. 4), in 2017, the final SOC stocks measured for NT-PM1 and CT-SV treatments were 11.3, and 10.8 Mg C ha^{-1} while RothC predicted 13.5 and 9.4 Mg C ha^{-1}. In both datasets, one can identify a tendency for RothC to underestimate the carbon stocks in conventional tillage treatments in the melon crop.

The model's statistical performance for each treatment is presented in Table 3. Overall, the model described the change of SOC stocks very well. The relative RMSE was low, ranging from 5 to 18%, indicating that there is a low relative difference between observed and predicted SOC. The MD, mean difference (also called Bias), ranged from −0.73 to 1.13 Mg C ha^{-1}. Across all treatments the t values were lower than the critical two-tailed 2.5% t-value, which means that the bias is not significant.

For Mango the model performed very well, showing high EF values (0.72 and 0.94), which is also true for most treatments of the Melon

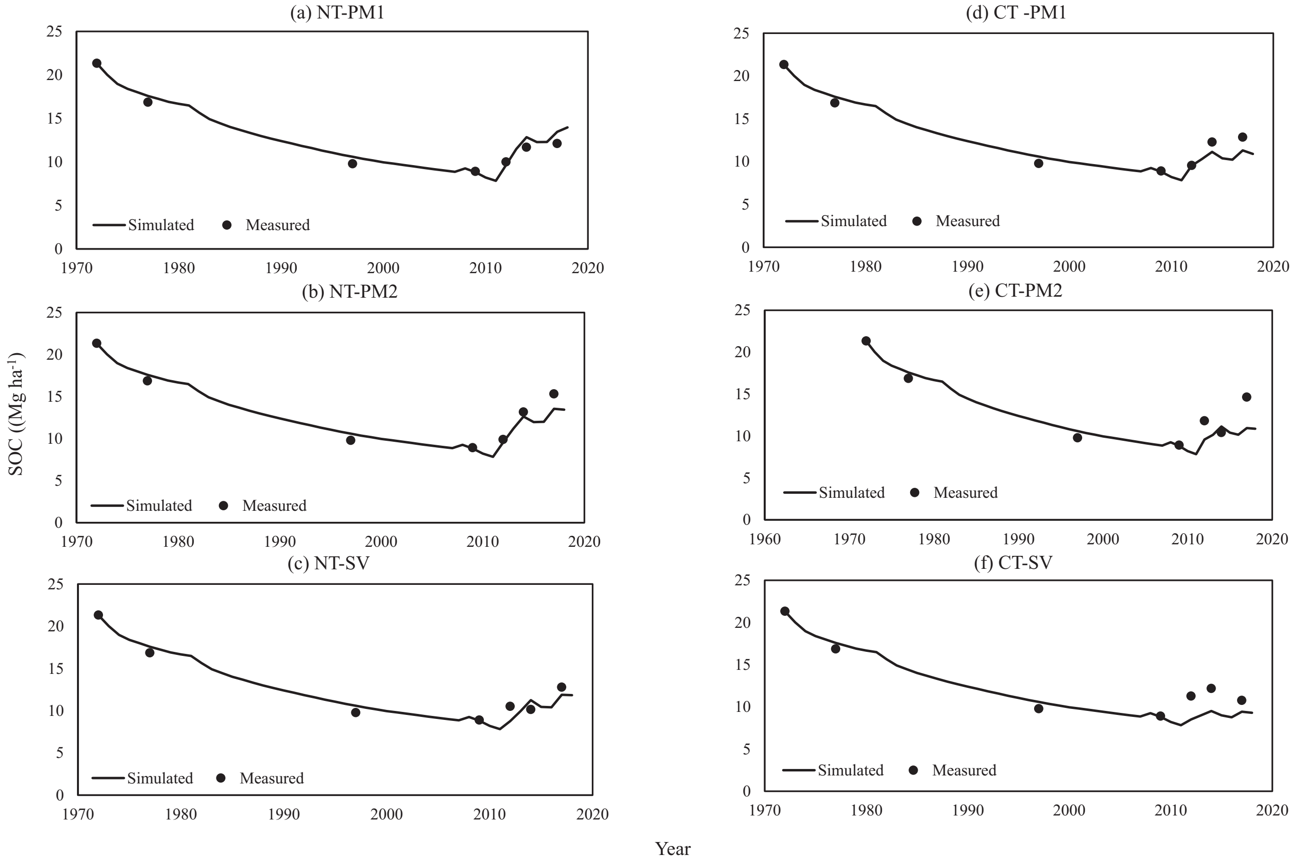

Fig. 4. Modelled (lines) and measured (symbols) SOC in the 0–20 cm layer from the data set the of long-term field experiment with Melon in the Brazilian Semiarid, using the RothC model. Legend: PM1–75% legume species + 25% grass/oilseed species, PM2–25% legume species + 75% grass/oilseed species; and SV, spontaneous vegetation, all under conventional (CT) and no-till (NT).

Table 3
RothC model statistic performance in twelve designs of multifunctional agroecosystems to semiarid irrigated areas using mango orchard as a model of perennial cultivation (Mango), and melon crop as a model of annual cultivation (Melon), included data from chronosequence and long-term field experiment.

Treatment	n	RMSE[a] (%)	MD[b] (Mg C ha^{-1})	EF	r
Mango[c]					
NT-PM1	6	8	−0.73	0.72	0.96
NT-PM2	6	10	−0.73	0.72	0.97
NT-SV	6	5	−0.36	0.92	0.98
CT-PM1	6	12	0.31	0.94	0.91
CT-PM2	6	5	−0.34	0.93	0.98
CT-SV	6	12	0.43	0.89	0.91
All treatments	21	12	−0.20	0.81	0.82
Melon[c]					
NT-PM1	6	10	−0.73	0.53	0.96
NT-PM2	6	7	−0.20	0.97	0.96
NT-SV	6	9	−0.02	1.00	0.94
CT-PM1	6	8	0.21	0.96	0.95
CT-PM2	6	15	0.63	0.70	0.81
CT-SV	6	18	1.13	−0.08	0.81
All treatments	21	8	0.22	0.31	0.89
All sites	40	10	0.14	0.52	0.84

PM1–75% leguminous species + 25% grass and oilseed species; PM2–25% leguminous species + 75% grass and oilseed species; and SV-spontaneous vegetation; NT - no-till; CT - conventional till. r = correlation coefficient; RMSE = root mean square error; MD = model mean difference; EF = model efficiency. EF ranged −∞ to 1, if EF = 1 the predicted values perfectly match the measures values.

[a] RMSE values are lower than RMSE (95% confidence limit) and the error is not significative.

[b] t values are lower than the critical two-tailed 2.5% t value and the bias is not significative.

[c] The SOC in the Caatinga, which was used to initialise the model in inverse mode, was discarded in the statistical analyses because it is not an independent value.

experiment (Table 3). However, the model underestimated SOC enrichment in some CT treatments (EF down to −0.08). The positive values of EF indicate that the modelled values describe the trend in the measured data better than the mean of the observations in most of the treatments. The correlation coefficient (r) ranged from 0.81 to 0.98 ($p < 0.05$).

The RothC model performance was evaluated by comparing the simulated values with those measured and for all Mango and Melon ($n = 21$ each) and, pooling Mango and Melon ($n = 40$) treatments in order to increase the robustness of the analysis. When both data sets are considered, the overall relative RMSE is low, indicating that there is a low difference between observed and predicted SOCs. The EF of the model is higher for the Mango (0.81) than in the Melon data set (0.31) but pooling both experiments EF increased to 0.52 (Fig. 5, Table 3).

3.3. Long-term impacts of agroecosystems' management on SOC stocks

The observed development of SOC was extrapolated into the future (2019 to 2069) using the calibrated RothC model. The modelling shows that under current climatic conditions the proposed agroecosystems have significantly different trends (Fig. 6). All NT scenarios are approaching the Caatinga equilibrium (21.3 Mg C ha^{-1}) but SV less effectively. Under Mango, only two of the six designs are likely to reach or exceed the SOC stocks for Caatinga within 30 years (Fig. 6a). The best performance was under NT for both plant mixtures: NT-PM1 and NT-PM2. Our data address the importance of NT in perennial systems, considering that there is no significant difference between the carbon input for NT and CT designs (ca. 5 Mg C ha^{-1} $year^{-1}$; Table 2). The SV associated with tillage is likely to have the worst result (CT-SV), even further decreasing SOC stocks. In contrast, NT-SV is likely to add about 50% of its residues (2.62 Mg C ha^{-1} $year^{-1}$) while

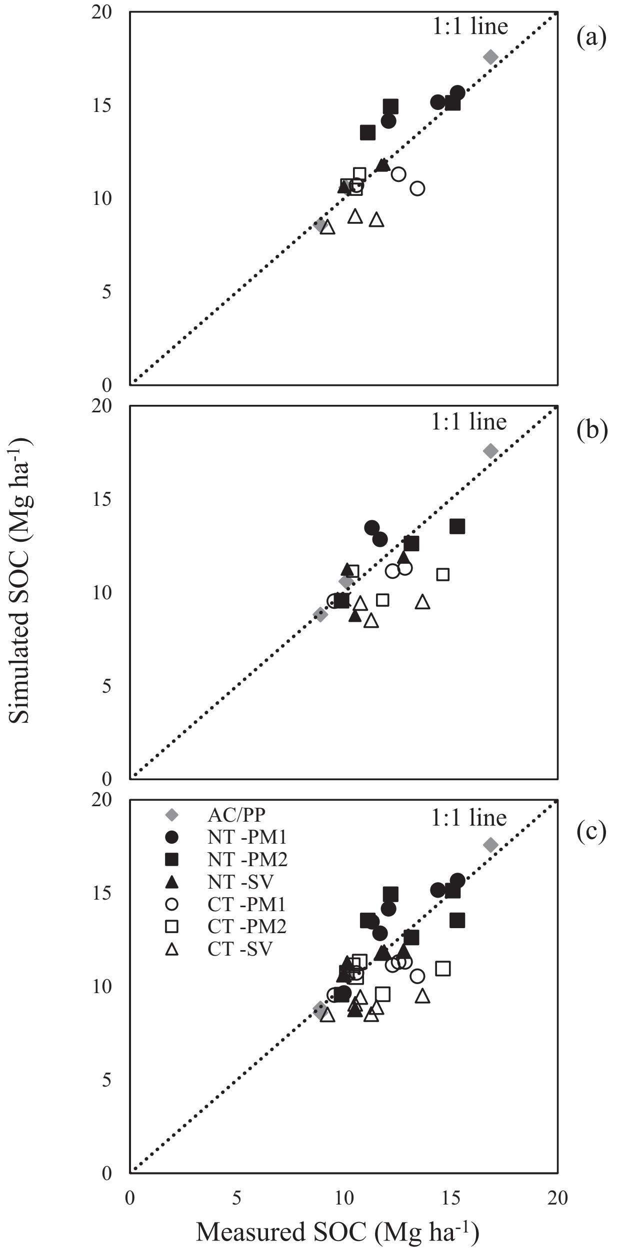

Fig. 5. Measured and simulated SOC in the 0–20 cm layer with all Mango (a), Melon (b) and, Mango plus Melon treatments (c) from the data set of the long-term field experiments, using the RothC model. Legend: AC - annual crop; PP - palm plantation; PM1–75% legume species + 25% grass/oilseed species, PM2–25% legume species + 75% grass/oilseed species; and SV, spontaneous vegetation, all under conventional (CT) and no-till (NT).

expensive plant mixtures combined with tillage are wasted (inputs of 4.90 and 4.76 Mg C ha^{-1} year^{-1} for CT-PM1 and CT-PM2, respectively; Table 2).

Three out of six treatments applied to the Melon agroecosystem are likely to reach the same SOC as Caatinga after 50 years (Fig. 6b). The NT-PM designs are able to reach previous Caatinga SOC stocks after little more than two decades (20 to 23 years, respectively), which is due to high C inputs (5.56 Mg C ha^{-1} year^{-1}) from PM and melon residues (NT-PM1, NT-PM2, CT-PM1, and CT-PM2). Comparable designs for Mango added only 4.89 Mg ha^{-1} year^{-1}, increasing SOC stocks slightly less, e.g. 0.49 compared to 0.56 Mg C ha^{-1} year^{-1} in Melon. The difference in terms of C inputs between Melon and Mango was 0.67 Mg C ha^{-1} year^{-1}, and the annual increase of soil carbon was 0.07 Mg ha^{-1} year^{1}.

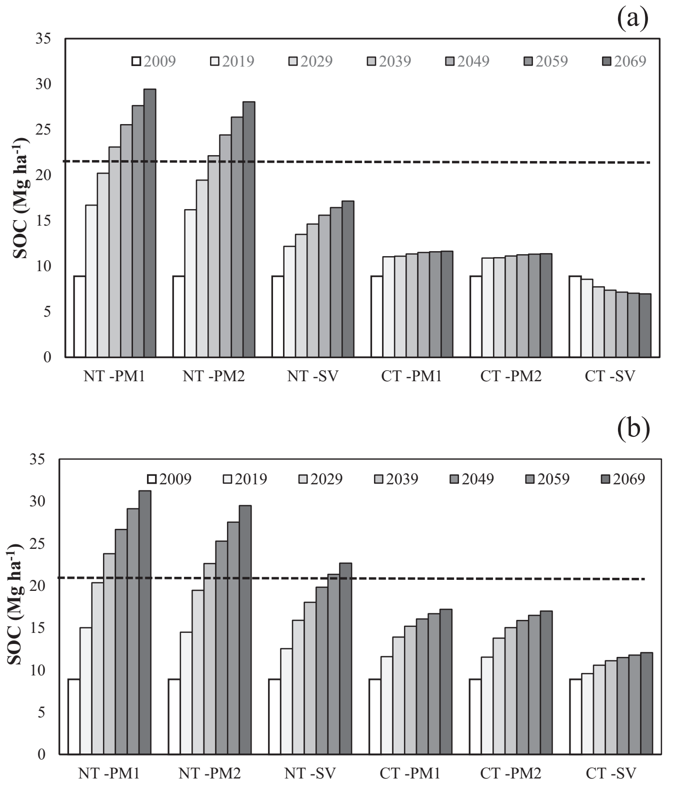

Fig. 6. Predicted soil organic carbon by RothC 2.3 model in six designs for Mango representing perennial cultivation (a) and six designs for Melon representing annual cultivation (b). Legend: PM1–75% legume species + 25% grass/oilseed species, PM2–25% legume species + 75% grass/oilseed species; and SV, spontaneous vegetation, all under conventional (CT) and no-till (NT); dashed line represents steady state Caatinga bushland.

Under NT-SV the Caatinga equilibrium is likely to be reached in five decades (47 years).

4. Discussion

4.1. Land use and agroecosystems design to increase soil carbon stocks

In this paper, we show a sustainable approach of land management for the semi-arid regions to increase the SOC content by designing multifunctional agroecosystems. We used experimental evidence for different cover crop mixtures and soil tillage for perennial (Mango) and annual crops (Melon) in irrigated dryland ecosystems. This partially reversed the impact of deforestation and conventional agricultural systems that had reduced the SOC stocks in the semi-arid region (Sacramento et al., 2013; Santana et al., 2019; Valbrun et al., 2018). The conversion of Caatinga forest into mixed arable and perennial (date palms) agriculture had caused substantial carbon losses during a period of 35 years. Cover crop systems combined with NT were able to reverse the loss of SOC in both, Mango and Melon production systems (Table 3). The SOC stocks (0-20 cm soil layer) increased between 0.041 and 1.068 Mg C ha^{-1} year^{-1}, peaking in the NT-PM2 treatment for Melon and being least in the SV-CT treatment for Mango in spite of high annual C additions (5.14 and 2.55 Mg C ha^{-1} year^{-1}, respectively). Overall, the highest rates of SOC increase occurred in agroecosystems combining PM with NT.

Different mixed system approaches have been shown to increase SOC in semi-arid and arid regions, e.g. the presence of trees in grassland (Mureva et al., 2018). Negative correlations between precipitation and SOC accumulation show the limitation of CT-systems without cover crops (García-González et al., 2018). Irrigation is crucial to enhance biomass production in dryland ecosystems (Lal, 2004) but must be combined with SOC conservation. However, little research has been conducted in irrigated semi-arid areas with the aim of sustainable intensification of semi-arid agroecosystems, a gap this paper has addressed.

With variable success, we implemented the concept of multifunctionality by combining different types of cover crops with reduced tillage to demonstrate their impact on SOC stocks (Giongo et al., 2016; Müller Carneiro et al., 2018; Santos et al., 2018). Our results were confirmed by García-González et al. (2018) who showed that ten years of irrigated cover crop cultivation increased the SOC stocks in the 0-20 cm layer by 0.42 and 0.18 Mg C ha^{-1} $year^{-1}$ under reduced and conventional tillage, respectively. This was independent of the type of cover crop (barley, vetch), C input for both being similar (1.6 Mg C ha^{-1-} $year^{-1}$). Our data showed the combined effect of tillage reduction and total C input from plant mixtures of different quality. The higher mean annual temperatures in the Brazilian Semi-arid (26.2 °C compared to 14.6 °C in Spain) and irrigation accelerate the decomposition process (Freitas et al., 2019; Pereira Filho et al., 2019). However, changes to NT combined with high input PM are the main controls for mitigating SOC losses. Economically, savings in tillage could compensate costs of special PM seeding material.

Normally, loss of yield, higher costs, and lower profitability are the main concerns of the farmers in adopting new agroecosystems designs. However, our results and previous studies in these trials (Santos et al., 2018; Müller Carneiro et al., 2019) show that NT and the PM can increase or maintain crop yields (Fig. S1, Supplementary Material) and profitability of mango orchards and melon crops.

Plant mixtures increased mango yields independent of soil management as the long-term economic analysis showed: PM generated higher revenue and profits than the conventional system (Müller Carneiro et al., 2018). In Melon, PM increase the productivity mainly when NT is implemented (Santos et al., 2018); they also compared the experimental data from PM2-CT with the conventional systems (CT-SV) adopted by farmers, showing higher costs in PM2-CT were offset by higher yields and NT increased profits due to lower costs.

4.2. Roth C model

The SOC stocks measured under Caatinga vegetation (21.3 Mg C ha^{-1}) was well modelled using the standard settings in RothC, only slightly adjusting C inputs during the spin-up runs (Figs. 3 and 4). This first step is essential for the initialisation, which has a significant influence on subsequent RothC model outputs. Residue inputs are important and should be estimated as accurately as possible (Nemo et al., 2017). Data on aboveground biomass of the Caatinga vegetation were based on those previously described by Lima Júnior et al., 2014. The SOC stocks (0–20 cm) are naturally low, the average is 23 Mg C ha^{-1} (Menezes et al., 2012) with a range from 17 Mg C ha^{-1} (Schulz et al., 2016) to 30 Mg C ha^{-1} (Althoff et al., 2018). Biomass formation and residue inputs are limited by water and soil fertility in this system, resulting in small SOC contents.

The soils of the experiments in the present study have high sand and very low clay contents, characterized as "sandy loams" (Table 1). Carbon turnover in RothC is sensitive to high sand contents in soil and successfully simulated our experimental results (Table 3). Similar results have been found in similar land management regimes (tillage intensities × fertility) in African sandy soils (>70% sand, <8% clay) (Mujuru and Hoosbeek, 2016). Due to the extremely dry climate in our study area, irrigation water must be added to produce a crop, guarantee C inputs and carbon turnover simulated by RothC.

The RMSE ranged from 5 to 18% and were within $RMSE_{95\%}$ limits. The low values of RMSE indicated that there was a small difference between the observed and predicted SOC by RothC, which is important as *RMSE* is considered one of the best statistical indicators to measure the model performance (Senapati et al., 2014).

MD values showed a significant bias specifically in the NT-PM1 and CT-PM1 under Melon but not for Mango. This may be due to the effect of melon residues retarding the decomposition of green manure (PM). There was no overall significant bias for the other treatments, the values ranging from −0.73 to 1.13 Mg C ha^{-1} over 8 or 6 years, respectively. Under Mango, across all six treatment designs the EFs were satisfactory, ranging from 0.72 to 0.94 over 8 years. Under Melon, EF values were positive in five out of six treatments, and low, even negative in the CT-SV. The positive EFs indicated that simulated values are better than the measured mean (Smith et al., 1996). Additionally, the observed versus modelled SOC contents are highly correlated (r) indicating significant positive associations between modelled and measured SOC values ($p < 0.05$). The statistics show clearly that the model has a very small overall uncertainty and therefore the model can be used with confidence at other sites with similar soil, climate and management conditions. Overall, the RothC modelling approach represents a promising method to estimate SOC in irrigated semi-arid areas (Senapati et al., 2014) and variable cover crops (Yao et al., 2017; Zhang et al., 2019). We showed that it can be used to estimate the SOC changes according to differences in agroecosystem management (Table 3). This confirms that RothC can model the soil management effects in irrigated dryland agriculture and discriminate designs of multifunctional agroecosystems, affecting SOC dynamics. This adaptation of the model may bring further benefits not only to studies in his region but also for modelling other tropical dryland ecosystems of the world.

4.3. Future SOC under intensified multifunctional agroecosystems

Our future scenario simulations were based on the fact that RothC can describe well the SOC decay for the land use transition from Caatinga to conventional management and its recovery for various "cover crop × tillage combinations". For the simulations we assumed that future climatic conditions would be similar to the current climate. The scenario results showed that Mango cultivated with cover crops and NT can reverse previous losses of SOC stock within thirty years using leguminous plant mixtures (75 or 25% legumes; Fig. 6a and b). Results from scenarios with Melon were even better due to the likely higher crop residue inputs compared to Mango (Table 2), concluding that NT + PM is the only way to increase SOC in perennial systems. Overall however, reducing soil tillage is the most important factor required to increase SOC stocks in irrigated systems (Fig. 6). The results also show that the quantity and quality of the residues were less significant for the increase SOC stocks than the tillage regime. Our results are supported by several studies for the semi-arid regions (García-González et al., 2018; Pereira Filho et al., 2019; Zhang et al., 2013) that demonstrated an increase in total SOC stocks promoted by changes in land management (Aquino et al., 2017; Valbrun et al., 2018).

For the Melon system, PM treatments combined with NT reached the SOC stocks of the Caatinga forest after only 23 years while the recovery under NT-SV is expected to take five decades (Fig. 6b). Leguminous plant mixtures and Melon residues added on average 0.7 Mg ha^{-1} $year^{-1}$ more C compared to Mango. In addition, plant mixtures are sown only in between rows between Mango trees, while they are sown in sequence to Melon over the whole field, resulting in spatial and temporal difference that are simplified in the model. Overall, in our system, average SOC accumulation rates are in the range estimated using RothC at the regional level in Spain (Jebari et al., 2018) which predicted an increase of SOC stocks of between 0.47 and 0.35 Mg C ha^{-1} $year^{-1}$ under climate change for NT combined with cover crops in irrigated row crops.

Finally, differences in plant litter chemistry, decomposition and accumulation rate can be attributed to vegetation-type which in RothC is represented by the DPM/RPM ratio (Yao et al., 2019, 2017; Zhang et al., 2019). Specific DPM/RPM ratios (which describe the decomposability of the actual residues) for plant materials used should model SOC turnover better than default values (Shirato and Yokozawa, 2006;

Zimmermann et al., 2007). The evidence that litter chemistry controls SOC over timescales of decades is ambivalent (Lützow et al., 2006; Poeplau and Don, 2015). Our simulations using a wide DPM/RPM ratio for C inputs from green manure (adding more DPM) clearly reduced SOC accumulation rate in comparison to simulations using the narrow default ratio. In their meta-analysis with data from 37 different sites, Poeplau and Don (2015) found that cover crops can increase SOC stock by an average annual rate of 0.32 ± 0.08 Mg C ha^{-1} $year^{-1}$ (soil depth of 22 cm). They concluded that 50% of the gain in SOC stocks is expected to occur within the first two decades. According to Althoff et al. (2018) and Araújo Filho et al. (2018), it would need 50 to 80 years under current climate conditions to recover the SOC stock in Caatinga forests. Our multifunctional irrigated agroecosystems combining NT and leguminous plant mixtures can recover the SOC in less than half of this timespan.

Last not least, three thoughts regarding the multi-functionality of the proposed agroecosystem: First, the intensification is entirely based on the assumption that the availability of irrigation water is warranted in the future. If this is the case at large scale, the proposed intensive management of horticultural crops will cool this semi-arid region, perhaps affecting its rainfall. Secondly, our C analysis considers SOC only, but not woody aboveground and belowground biomass C, which over the life-time of the Mango system would accumulate and reduce the difference between Melon and Mango. Lastly Mango wood could be a renewable source of biofuel.

5. Conclusions

We have shown that the design of multifunctional agroecosystems (plant mixtures × tillage × annual/perennial) is able to increase SOC stocks (0–20 cm) when irrigated in the range of 0.041 (low input Mango, CT) and 1.068 Mg C ha^{-1} $year^{-1}$ (high input Melon, NT). We have shown that leguminous plant mixtures and reduced tillage for annual or perennial crops can increase SOC. During the next five decades and assuming stable climatic conditions, the SOC of nearby native Caatinga forest (21.3 Mg C ha^{-1}) can be achieved under both crops by combining cover crops and NT within 23 to 27 years. We used RothC with a daily timestep to simulate the wetting and drying of the soil throughout the year, irrespective of irrigation.

CRediT authorship contribution statement

Vanderlise Giongo: Conceptualization, Methodology, Validation, Writing - original draft. **Kevin Coleman:** Conceptualization, Software, Methodology, Writing - review & editing. **Monica da Silva Santana:** Data curation, Formal analysis. **Alessandra Monteiro Salviano:** Data curation, Investigation, Formal analysis. **Nelci Olszveski:** Data curation. **Davi Jose Silva:** Data curation, Investigation. **Tony Jarbas Ferreira Cunha:** Data curation, Investigation. **Angelucia Parente:** Data curation. **Andrew P. Whitmore:** Methodology, Writing - review & editing. **Goetz Michael Richter:** Conceptualization, Methodology, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.138072.

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