PastorC-Tambo: a simplified model to assess carbon balance of dairy farms

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ABSTRACT

Grazing systems have the potential to mitigate greenhouse gas (GHG) emissions and improve C balance through soil C sequestration. The inclusion of soil organic carbon (SOC) balance in farm scale models is needed to assess the C balance of grazing dairy systems. The objective of this work was to present and evaluate the sensitivity of a simplified model developed to estimate C balance of dairy production systems in the Pampas region of Argentina. The model, called PastorC-Tambo, combines three interrelated sub-models: a sub-model of dry matter intake (DMI), a sub-model of GHG emissions, and a sub-model of SOC balance. To assess the sensitivity of the model, different forage productivities (high: 18, 7.5, and 27 t DM/ha, medium: 12, 5 and 18 t DM/ha, and low: 6, 2.5, and 9 t DM/ha for alfalfa, oat, and maize silage, respectively), concentrate supplementation levels (350, 250, and 150 g/l milk for high, medium, and low, respectively), stocking rates (from 0.27 to 3.56 cows/ha, with use efficiencies of 25, 45, 65, and 85%), effluent treatment system, and milking time, were simulated for representative dairy production systems. C balance estimates ranged between -2.54 and 0.64 t C/ha. Balance improved with the rise in forage productivity and declined as stocking rates increased. Increased concentrate supplementation improved C balance at constant forage productivity and stocking rate. Effluent treatment systems also affected C balance. Storage in anaerobic lagoons had the lowest C balance, while the inclusion of solids separation and agronomic reuse improved it. Anaerobic digestion also increased the C balance compared to anaerobic lagoons. PastorC-Tambo proved to be sensitive to changes in the C balance of commercial dairy farms in the Pampas region of Argentina.

Keywords: sustainability, carbon sequestration, greenhouse gas emissions.

RESUMEN

Los sistemas ganaderos pastoriles tienen el potencial de mitigar las emisiones de gases de efecto invernadero (GEI) y mejorar el balance de C mediante el secuestro de C en el suelo. La inclusión del balance de carbono orgánico del suelo (COS) en modelos de escala predial es necesaria para evaluar el balance de C de los sistemas lecheros pastoriles y de base pastoril intensificados. El objetivo de este trabajo fue presentar y evaluar la sensibilidad de un modelo simplificado desarrollado para estimar el balance de C de sistemas de producción de leche bovina de la región Pampeana. El modelo, denominado PastorC-Tambo, combina tres submodelos interrelacionados: un submodelo de consumo de materia seca (CMS), un submodelo de emisiones de GEI y un submodelo de balance de COS. Para evaluar la sensibilidad del modelo se simularon diferentes productividades del forraje (alta: 18, 7,5 y 27 t MS/ha, media: 12, 5 y 18 t MS/ha, y baja: 6, 2,5 y 9 t MS/ha, para alfalfa, avena y ensilaje de maíz, respectivamente), niveles de suplementación con concentrado (350, 250 y 150 g/l de leche para alto, medio y bajo, respectivamente), carga animal

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(entre 0,27 y 3,56 vacas/ha, simulando eficiencias de aprovechamiento en pastoreo de 25, 45, 65 y 85%), sistemas de tratamiento de efluentes y tiempos de ordeño para un sistema lechero representativo de la región. Las estimaciones del balance de C variaron entre -2,54 y 0,64 t C/ha. El balance mejoró con el aumento de la productividad del forraje y disminuyó a medida que aumentó la carga animal. A productividad del forraje y carga animal constantes, el aumento en el nivel de suplementación con concentrado mejoró el balance de C. Los sistemas de tratamiento de efluentes también tuvieron efecto sobre el balance de C. El almacenaje de efluentes en lagunas anaeróbicas presentó el balance de C más desfavorable, mientras que mejoró con la inclusión de separación de sólidos y reutilización agronómica. La digestión anaeróbica para la producción de biogás también mejoró el balance de C en comparación con las lagunas anaeróbicas. PastorC-Tambo demostró ser un modelo sensible para evaluar el balance de C en sistemas comerciales de producción de leche bovina de la región Pampeana.

Palabras clave: *sustentabilidad, secuestro de carbono, gases de efecto invernadero.*

INTRODUCTION

Climate change challenges dairy farms to reduce their GHG emission intensity and, more importantly, their absolute emissions (FAO and GDP, 2018). Although most mitigation strategies have been evaluated for confined or semi confined systems (Beauchemin *et al*., 2022), grazing systems have the potential to mitigate GHG emissions by enhancing soil carbon capture and sequestration, as it is one of the largest carbon sinks (Conant *et al*., 2017; Clivot *et al*., 2019). Previous research has shown that improved grassland management increases SOC (Conant *et al*., 2017). Another pathway for GHG emissions mitigation is through manure and effluent management. This could be reached by reducing manure GHG emissions with improved treatment systems, but also by the agronomical reuse of manure to contribute to SOC balance (Herrero, 2014; FAO and GDP, 2018; Whitehead *et al*., 2018; IPCC, 2019).

In grazing systems, there are various and complex tradeoffs occurring between production (e.g., grazing efficiency and stocking rate) and environmental outputs (e.g., C returned to soil and GHG emissions) that must be balanced to optimize management systems towards sustainability (Soussana and Lemaire, 2014). Simulation models, adapted to local agroclimatic conditions, can help address this complexity and evaluate C balance of dairy production systems (Bhattacharyya *et al*., 2021; Faverin and Tieri, 2023). Models based on the IPCC (2019) assume that SOC is in equilibrium, and hence, soil sequestration capacity is not considered. Thus, considering the mentioned tradeoffs, the development of simple and sensitive farm scale models is required to properly evaluate the sustainability of grazing dairy systems (Soussana and Lemaire, 2014), which are the predominant dairy system type in the Pampas region of Argentina (Lazzarini *et al*., 2019; Engler *et al*., 2022).

The first goal of this work was to present a simplified farm model called PastorC-Tambo to estimate C balance of dairy production systems in the Pampas region of Argentina. A second goal was to evaluate the sensitivity of the model to variations in stocking rates, productivity, and management of grazing resources, as well as different effluent treatment systems frequently used in this region.

MATERIALS AND METHODS

Model description

PastorC-Tambo was developed using MS Excel (Microsoft, Washington, USA) to estimate SOC balance, GHG emissions, and C balance (including SOC balance and GHG emissions) of dairy production systems in the center and north of the Pampas region of Argentina.

The model requires data entry according to the farm's land use (field scale) and herd subdivisions (category or group scale). Land use and forage data inputs for each field are: forage species, grazing (used or not used for grazing), field surface, soil organic matter (SOM) and bulk density from the upper 20 cm layer, tillage system, average aerial biomass growth rate, digestibility, and time of use. The model also requires the proportion of dry matter (DM) production that is used for forage reserves. Herd data inputs for each category or group are: number of animals; mean live weight; duration; milk production and fat content; feeding system (grazing or confined); diet composition (both for supplements and total diets); and quantity offered. Adjustments can be made related to the animal (sex, age, frame, body condition score), the diet (intake restriction, use of additives, substitution rate) and environmental conditions (temperature, mud).

For milking and dry cows, the combination of grazing with confined periods can be selected as a feeding system since it is a common practice on regional dairy farms (Bretschneider and Salado, 2010). If this feeding system is selected, daily confinement time is required. Calving interval, milking time, and the effluent treatment system used (storage in anaerobic lagoons, solid separation before anaerobic lagoons and solid reuse, daily spread, and anaerobic digestion for biogas production) are also required as general management information.

PastorC-Tambo combines three interrelated sub-models: a first for DMI, a second for GHG emissions, and a third for SOC balance (figure 1).

The first sub-model estimates DMI for each group based on animal, diet, and environmental characteristics (adapted from Fox *et al*., 1988; Fox *et al*., 2004). PastorC-Tambo estimates grazing DMI using the total predicted DMI, supplementation level, and substitution rates of grazing groups.

The second sub-model estimates GHG emissions, which are limited to CH_4 emissions from enteric fermentation and feces, as well as direct and indirect N_2O emissions from feces and urine. These estimations were adapted from IPCC (2019, see Appendix). GHG emissions are converted to CO_2 equivalents, considering greenhouse power 28 and 265 times greater than CO_2, for CH_4 and N_2O, respectively (IPCC, 2014). Then, CO_2 equivalents are converted to C using a factor of 0.273 kg C/kg CO_2 (Viglizzo *et al*., 2019). Other GHG emissions (e.g., use of fossil fuels) are not considered in the model, in order to maintain its simplicity and applicability.

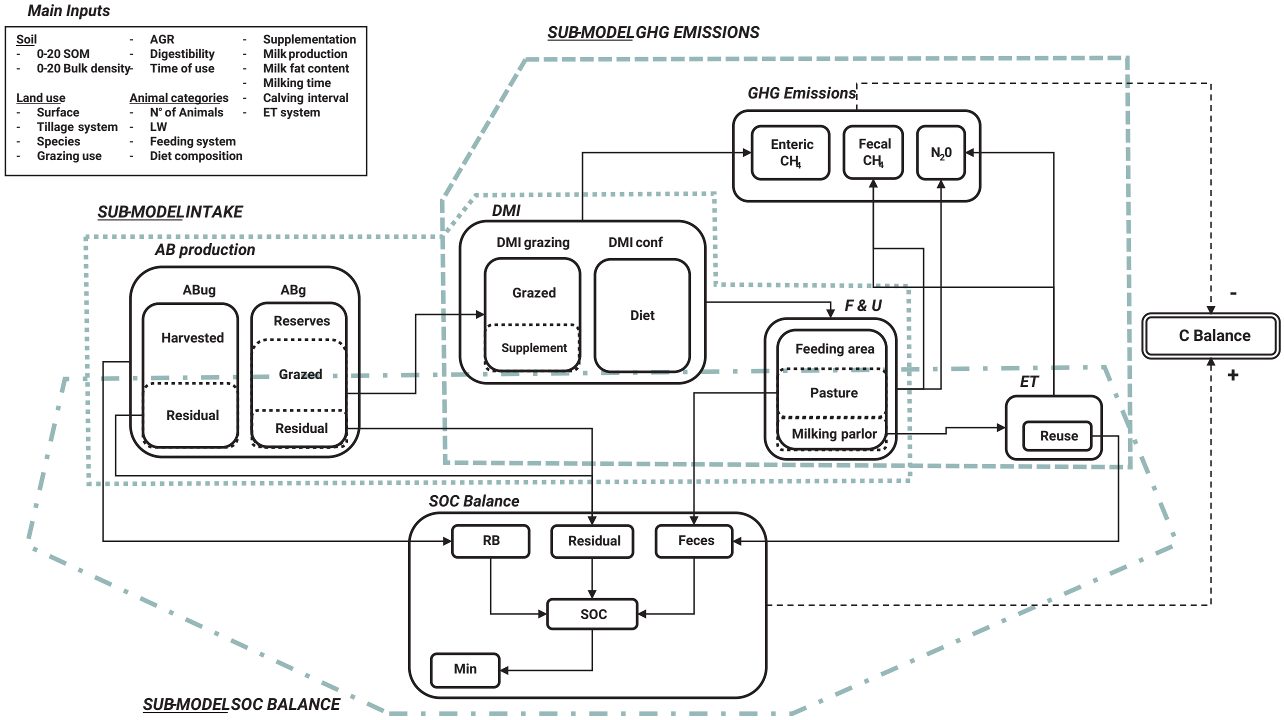

Figure 1. Conceptual diagram of the flows considered in PastorC-Tambo. AB: aerial biomass production, ABg: aerial biomass from grazed resources, ABug: aerial biomass from ungrazed resources, AGR: average aerial biomass growth rate, conf.: confinement, DMI: dry matter intake, ET: Effluent treatment, F & U: Feces and urine, GHG: greenhouse gas, LW: live weight, Min: mineralization, RB: root biomass, SOC: soil organic carbon, SOM: soil organic matter.

The third sub-model is used to calculate the SOC balance. It was adapted from the model proposed by Hénin and Dupuis (1945), which consider that C inputs are incorporated into a unique SOC fraction. There are more complex models that divide SOC into label and stable fractions (Andriulo *et al*., 1999; Irizar *et al*., 2015). Moreover, recent research highlighted the importance of root exudates in the SOM stable fraction (Villarino *et al*., 2021), which could lead to more complex and precise models. However, even though the estimation of these fractions may increase predictions´ precision, it would require more complex information inputs (label and stable SOC initial values that are not normally available), jeopardizing the simplicity and applicability pretended for PastorC-Tambo.

The SOC sub-model requires information derived from the main inputs and DMI sub-model, to estimate: residual aerial biomass (ABres) after grazing, root biomass on the top 20 cm of soil (RB), and feces (Liu *et al*., 2011). Carbon content of the inputs´ DM is defined as 0.45 t C/kg DM (Liu *et al*., 2011). Each input is affected by different humification coefficients (k_a, k_r, and k_f, for ABres, RB, and feces, respectively), with k_a being a function ranging between 0.16 and 0.31, decreasing with the increase of ABres, $k_r = 0.39$, and $k_f = 0.52$ (adapted from Clivot *et al*., 2019). These adjustments of k_a allow the model to be sensitive to differences in ABres of pastures.

The ABres is calculated using AB, grazing DMI, and reserves production. Grazed DMI and reserves production are discounted from AB for resources used for grazing. On the other hand, for resources not used for grazing, ABres is estimated by the difference between AB and harvested biomass.

Root biomass is estimated using a RB/AB ratio of 0.53 and 0.74, for annual and perennial species, respectively (Liu *et al*., 2011). For very low production resources, a minimal RB of 640 kg DM/ha is considered (adapted from Saffih and Maryb, 2008). Also, in order to adjust biomass to the top 20 cm layer, Fan *et al*. (2016) equations are used. Although the soil sink capacity could be considered for deeper layers, the local data used to characterize soil layers and adjust the mineralization rate coefficients considered the upper horizon at 20 cm depth (Irizar *et al*., 2015). Also, the restriction of SOC dynamics to the 20 cm topsoil layer seeks simplicity for the model and to facilitate soil data availability from commercial dairy farms since the typical soils of the Pampas region of Argentina present a 20 cm depth upper horizon.

The model takes into account feces production and distribution. DMI digestibility is used to calculate feces production [Feces = DMI * (1- Digestibility)]. Mean DMI digestibility of grazed pastures is adjusted by grazing use efficiency (adapted from Galli *et al*., 1999). Mean DMI digestibility of supplements and diets is calculated from the digestibility and proportions of each ingredient. Feces distribution is proportional to the time the animals spend in the different areas: pastures, feeding areas, or milking parlors (adapted from White *et al*., 2001). Feces deposited on pastures or other grazing resources are considered a SOC input, while those excreted on other feeding areas are not considered to return to soil (adapted from Liu *et al*., 2011).

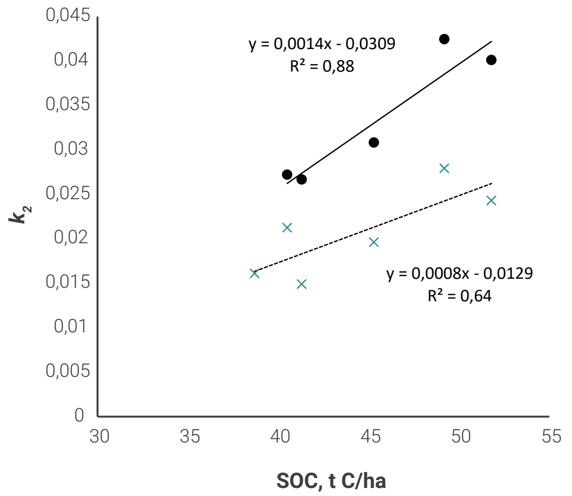

Figure 2. Mineralization coefficient (k_2) as function of soil organic carbon (SOC) for no tillage system (gray crosses) and tillage system (black circles). Linear regressions equations were estimated using data from Irizar *et al*. (2015).

On the other hand, feces excreted in the milking parlor are considered or not a SOC input, depending on the type of effluent treatment system implemented. When effluents return to the pastures, the model considers them a SOC input. Also, if the effluent treatment system includes solid separation and reuse as fertilizer, the amount that returns to the soil depends on separation efficiency. For solid separation systems, three degrees of efficiency are established (high: 70%, medium: 40%, or low: 10%), due to the great variation that can exist within solid separation systems (Gooch *et al*., 2005).

The fraction of SOC lost by mineralization is estimated by PastorC-Tambo as the product of SOC and a mineralization rate (k_2), which is dependent on SOC and tillage systems (Irizar *et al*., 2015; figure 2). The annual balance between gain and loss of SOC (t C/ha/year) is calculated, resulting in positive values when the soil stores plant C, and negative values when it emits C into the atmosphere.

Finally, the total C balance of the system (t C/ha/year) is estimated as SOC balance minus GHG emissions. Again, when balance is positive, the whole dairy system captures C, and when the balance is negative, the system acts as a source of C to the atmosphere.

When SOC balance is positive, PastorC-Tambo calculates a “GHG mitigation index”, defined as the ratio between SOC balance and GHG emissions. This index represents the percentage of GHG emissions that could be mitigated by C capture in soil. When SOC balance is negative, the index is zero since there is no mitigation. A subjective scale using this index was defined to assess the environmental condition of the dairy production system (table 1).

As an example, PastorC-Tambo main inputs and outputs of a dairy farm with representative characteristics of the Pampas region of Argentina (Engler *et al*., 2022) are presented in table 2.

Sensitivity analysis

To assess the sensitivity of PastorC-Tambo to variations in stocking rates, productivity, and management of grazing resources, different pasture productivity levels, supplementation levels, and stocking rates were simulated for representative dairy production systems in the Pampas region of Argentina.

Simulations were carried out considering only the herd of milking and dry cows and the area used for these categories. The system was defined with alfalfa pasture, oat winter pasture, and maize used for silage, representing a land use of 62, 12, and 26%, respectively (adapted from Engler *et al*., 2022). Also, the simulation considered soils with a high organic matter content (3.5% of SOM) and 1.20 t/m^3 of bulk density, and no tillage system.

Three levels of forage productivity were simulated: high (AB = 18, 7.5 and 27 t DM/ha for alfalfa, oat and maize silage, respectively), medium (AB = 12, 5 and 18 t DM/ha for alfalfa, oat and maize silage, respectively) and low (AB = 6, 2.5 and 9 t DM/ha for alfalfa, oat and maize, respectively). In all productivity levels, 5% of alfalfa AB was used for reserves confection, and 95% harvest efficiency was defined for maize silage confection.

As regards herd characteristics, Holstein cows with 600 kg of live weight (frame 7) and a mean milk production of 20 l/day with 3.6% fat were defined. Also, a 400-day calving interval and a 0.83 milking cows/total cows ratio were considered (adapted from Engler *et al*., 2022).

Concerning the feeding system, milking cows were set as a grazing group, while dry cows were set as a confined group. Milking cows’ supplementation was established at 6.3 kg DM/day of maize silage and three levels of inclusion of commercial concentrates: 150, 250, and 350 g/l milk (3, 5, and 7 kg DM/milking cow/day, respectively). Substitution rate was fixed at 70%. Dry cows’ diet was fixed at 30.5% dry milled maize grain, 9.1% soybean meal, 26.1% maize silage, and 34.3% alfalfa hay. The ingredients´ composition was defined as the mean values reported by INTA (2020).

Stocking rates simulated ranged between 0.27 and 3.56 cows/ha in order to achieve use efficiencies of 25, 45, 65, and 85%. The range of stocking rates evaluated was similar to that reported by Engler *et al*. (2022). Milking time was fixed at 4 h/day, while the effluent treatment system selected was “storage in anaerobic lagoons”, which is the most typical system in the Pampas region of Argentina (Engler *et al*., 2022).

Besides, to assess the sensitivity of PastorC-Tambo to changes in effluent management, a model dairy farm was simulated with varying milking times (3, 4, 5 or 6 h/day) and effluent treatment systems (storage in anaerobic lagoons; low, medium, and high efficiency solid separation before anaerobic lagoon and solid reuse; daily spread; or anaerobic digestion for biogas production).

RESULTS

Productivity, supplementation level, and stocking rate

Simulations with PastorC-Tambo resulted in an increase in SOC balance with increasing pasture and forage production, with productivity being the factor with the greatest impact. Increasing forage productivity from medium to high (a 50% increase) enhanced SOC balance between 0.863 and 0.984 t C/ha/year. At low forage productivity (50% of medium productivity), SOC losses were obtained, ranging between -0.068 and -0.166 t C/ha/year (figure 3a).

Increasing stocking rates or use efficiency while maintaining the same forage productivity slightly changed SOC balance,

SOC Balance	GHG Compensation index	Rating	Interpretation
Increase	≥ 100 %	Very favorable	Total compensation of GHG emissions. The systems acts as a C sink
	≥ 67< 100 %	Favorable	High compensation of GHG emissions
	≥ 33 < 67 %	Regular	Medium compensation of GHG emissions
	> 0 < 33 %	Unfavorable	Low compensation of GHG emissions
Equilibrium or decrease	0%	Very unfavorable	No compensation of GHG emissions

Table 1. Greenhouse gas mitigation index rating and interpretation.

SOC: soil organic carbon, GHG: greenhouse gases.

Main Inputs

Land and Forage

	Surface, ha	Production, t DM/ha	Reserves, %	Tillage	Grazing use	SOM, %	Bulk density, t/m^3
Alfalfa	74,4	12	5	No tillage	yes	3,50	1,2
Oat	14,4	5	0	No tillage	yes	3,50	1,2
Maize silage	31,2	18	95	No tillage	no	3,50	1,2

Herd

	N° of animals	LW, kg	Feeding	Milk production, l/day	Milk fat content, %	Supplementation, kg DM/day	Maize silage, kg DM/day	Concentrate, kg DM/day
Milking cows	141	600	Grazing	20	3,60	12,1	6,3	5,8
Dry cows	29	600	Feedlot	-		11,8	3,1	4,7
Calving interval, days		400						
Milking time, h/day		4						
Effluent treatment		Storage in anaerobic lagoons						

Outputs

Biomass		SOC	t C/ha/year	GHG	t C/ha/year
AB grazing, kg DM/ha	10362	ABres	0,575	Enteric CH$_4$	1,187
Grazing DMI, kg DM/ha	5050	RB	0,799	Fecal CH$_4$	0,159
Grazing use efficiency, %	49	Feces	0,465	Direct and indirect N$_2$0	0,158
		Min	1,035	GHG emissions	1,505
		SOC balance	0,804		

C Balance, t C/ha/year	-0,701
GHG Mitigation index, %	53,43
Index value	Regular

Table 2. PastorC-Tambo main inputs and outputs. Simulation results for a representative dairy production system from the Pampas region of Argentina (Engler *et al*., 2022).

AB: aerial biomass, ABres: residual aerial biomass, C: carbon, DM: dry matter, DMI: dry matter intake, GHG: greenhouse gases, LW: live weight, Min: mineralization, RB: root biomass, SOC: soil organic carbon, SOM: Soil organic matter.

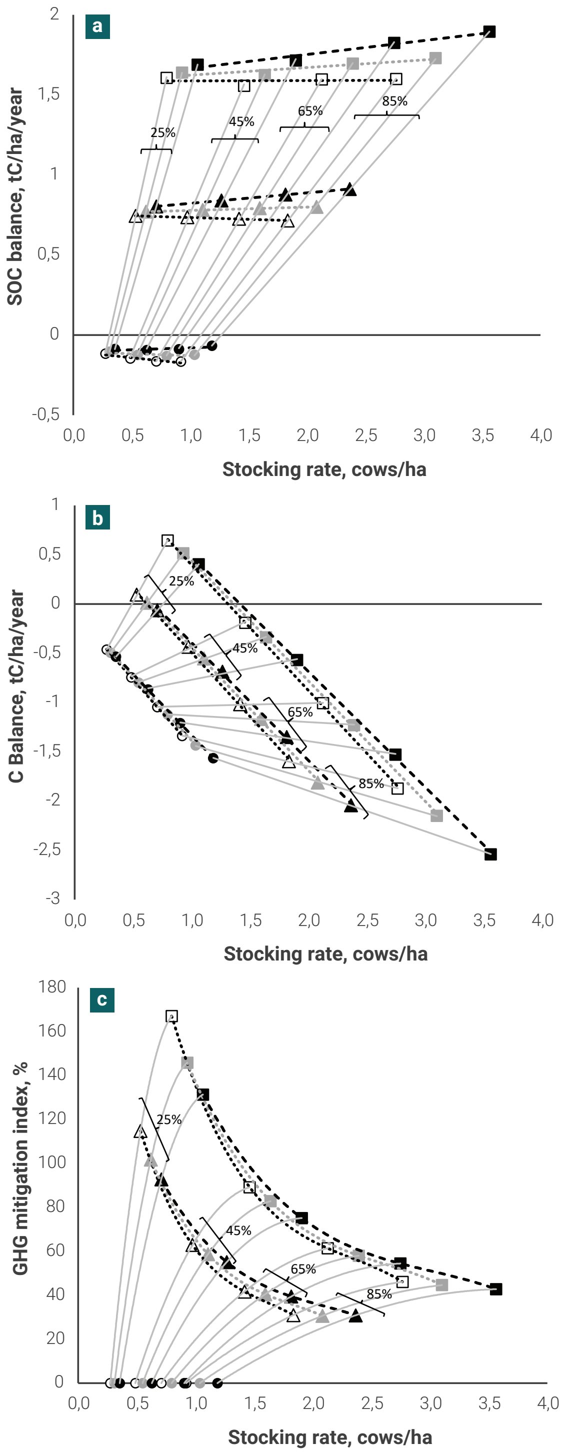

Figure 3. Soil organic carbon (SOC) balance (3a), total carbon (C) balance (3b), and greenhouse gas (GHG) mitigation index (3c) as function of stocking rate for different levels of pasture productivity and supplementation. The system was simulated with land use surface distribution of 62% alfalfa, 12% oat and 26% maize silage. High production (squares): 18, 7.5 and 27 t DM/ha; medium production (triangles): 12, 5 and 18 t DM/ha; low production (circles): 6, 2.5 and 9 t DM/ha, for alfalfa, oat and maize silage respectively. Commercial concentrate supplementation: high (black): 350 g/l milk, medium (gray): 250 g/l milk, and low (white): 150 g/l milk. Linear and polynomial regressions of output variables as functions of stocking rates at constant forage production and supplementation levels (black and gray dotted lines) and at constant supplementation level and grazing use efficiency (light gray dotted lines; 25, 45, 65, and 85%) are shown.

showing different responses depending on the supplementation level. In the cases with high supplementation rates (350 g/l milk), SOC balance tended to improve with the increase in stocking rate at medium and high forage productivities (0.066 to 0.088 t C/year/cow), while it remained relatively constant at low forage productivity. On the other hand, in cases with medium or low supplementation rates (250 and 150 g/l milk, respectively), SOC balance presented small variations with the increase in stocking rate (absolute change rate value 0.050 t C/year/cow). However, in the case of low supplementation combined with low forage productivity, the increase in stocking rate reduced SOC balance (-0.077 t C/year/cow).

The obtained C balance ranged between -2.54 and 0.64 t C/ha/year (figure 3b). The C balance improved with the increase in forage productivity, while it declined as stocking rates and use efficiency increased. Positive C balances were obtained for simulated systems with high and medium productivity of the forage resources together with low stocking rates (25% use efficiency).

At constant pasture and forage productivity and stocking rates, the increase in supplementation level improved C balance. Also, the decline in C balance with the increase in stocking rate was steeper with low supplementation (from -1.27 to -1.35 t C/year/cow) than with high supplementation (from -1.17 to -1.24 t C/year/cow).

The increase in forage productivity, maintaining grazing use efficiency (by increasing stocking rate), improved C balance for low to moderately low use efficiencies (25-45%). Whereas, at constant grazing use efficiency between moderately high and high (65-85%), C balance declined as forage productivity increased.

The GHG mitigation index was sensitive to changes in forage production and stocking rates (figure 3c), ranging from no mitigation with low forage production, to overcompensation with high and medium productivity grazed lightly (25% use efficiency). In cases with medium forage productivity, high mitigation (67-100% GHG mitigation) was achieved with moderately light stocking rates (<45% use efficiency), whereas with high forage productivity, it was achieved under moderate stocking (<65% use efficiency). Higher stocking rates reduced mitigation index to regular values (33-67% GMG mitigation).

Effluent treatment and milking time

PastorC-Tambo showed sensitivity to changes in effluent treatments and milking time (figure 4). The increase in milking time had a negative impact on the C balance of a modal dairy system in the Pampas region, except in cases where the daily spread system was simulated. The rate of C balance reduction ranged from -0.065 to -0.020 t C/ha/year per hour in milking time. However, with effluent daily spread, increasing milking time improved C balance by 0.007 t C/ha/year/hour.

The worst results were obtained for the anaerobic lagoon storage, while the inclusion of solid separation with agronomic reuse improved C balance. The improvement degree ranged from 0.019 to 0.268 t C/ha/year and depended on solid separation efficiency and milking time. The use of anaerobic digestion also improved C balance (compared with anaerobic lagoon), resulting in an intermediate situation between medium and high efficiency solid separation and reuse systems (improvement ranged between 0.121 to 0.243 t C/ha/year).

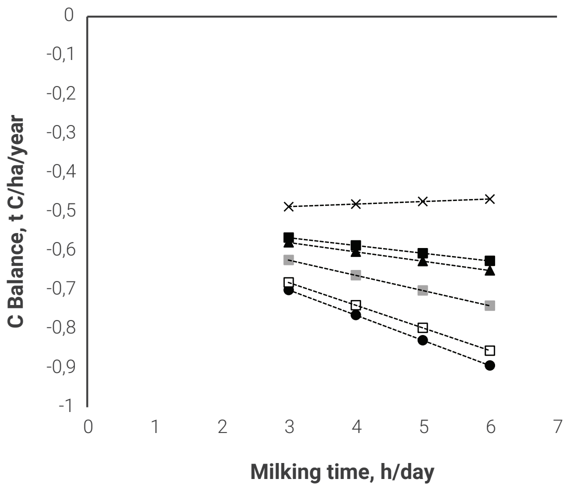

Figure 4. Carbon balance with increasing milking time and different effluent treatment system. Storage in anaerobic lagoon (circles); low (white squares), medium (gray squares), and high (black squares) efficiency solid separation before anaerobic lagoon and solid reuse; daily spread (crosses); and anaerobic digestion for biogas production (triangles). The system was simulated with area distribution of 62% alfalfa, 12% oat and 26% maize for silage. Forage production: 12 t DM/ha for alfalfa, 5 t DM/ha for oat, and 18 t DM/ha of maize. Supplementation: 288 g/l milk with a commercial concentrate. Linear regressions are presented with dotted lines.

DISCUSSION

Soil organic carbon balance

Grazing systems have the potential to sequester more C in soils than cropping systems (Franzluebbers, 2007). Generally, pastures obtain higher C inputs than annual crops, and C inputs are continuously deposited over time when grazing animals are included (Liu *et al*., 2011). SOC balance simulations ranged from -0.166 to 1.895 t C/ha/year, showing the sensitivity of PastorC-Tambo.

Conant *et al*. (2017) also reported that improved management practices (e.g., low stocking rates, rotational grazing, etc.) tended to increase SOC. These authors reported a mean increase of 0.47 t C/ha/year, ranging between 0.11 and 3.04 t C/ha/year, depending on the management improvement or practice and the experiment duration (years). Liu *et al*. (2011) reported that simulations using a model (*RothC*) presented close results compared with measured SOC balances. These authors indicated 0.46 and 0.57 t C/ha/year for annual and perennial pastures, respectively. Chan *et al*. (2010) also estimated a similar SOC balance for pastures in Australia, ranging from 0.26 to 0.72 t C/ha/year. The high pasture productivity potential in the Pampas region (Jauregui *et al*., 2022) helps explain the greater SOC balances predicted by PastorC-Tambo when simulating high forage productivity.

Pasture productivity was a major factor defining SOC balance in PastorC-Tambo simulations. This was expected since it would drive more production of residual biomass, root biomass, and C return by feces. Therefore, improving pasture productivity could increase C capture in the soil. In this sense, Chan *et al*. (2010) reported that P fertilization increased SOC balance by improving pasture productivity, when nutrient supply was limited.

Grazing management practices can also improve SOC balance through an increase in aerial and root biomass production. Conant and Paustian (2002) reported that overgrazed grasslands have the potential to sequester up to 1.83 t C/ha/year by reducing grazing intensities. A meta-analysis about the effect of grazing intensity on belowground carbon in grassland (Zhou *et al*., 2017) reported that light grazing increases SOC, while moderate and high grazing decrease SOC. In the same way, Jin *et al.* (2022) used ^{13}C markers and found that light grazing stimulated C allocation from shoots to roots, increasing root exudates and biomass, while heavy grazing reduced C allocation to roots and stimulated C transfer from the roots to the soil.

PastorC-Tambo simulations presented small changes with the increase in stocking rate (or grazing use efficiency) assuming a constant level of forage production. However, it must be taken into account that when stocking rates are too high, overgrazing reduces pasture production and consequently SOC balance (Conant and Paustian, 2002). The relative stability of SOC balance obtained by PastorC-Tambo simulations, with increasing stocking rates at constant forage production, suggests a tradeoff between a lower residual biomass and a higher feces production. However, the same pasture overgrazed would not produce the same AB, and thus, its SOC balance would be reduced (Conant and Paustian, 2002).

It is clear that forage production is a major factor defining PastorC-Tambo C balance simulations. Therefore, the model needs accurate estimations of pastures and different forage resources' productivity. Moreover, the model does not consider variations in C fluxes to roots due to grazing intensities. Therefore, the sensitivity relies on the differences in AB production, which remarks the importance of good predictions of forage production to feed the model.

Although some models estimate SOC balance for deeper layers (Clivot *et al*., 2019), the restriction of SOC dynamics to the 20 cm topsoil layer does not invalidate the results and conclusions obtained in response to the objectives of this work. Moreover, the extrapolation of the mineralization rate coefficients to deeper layers may be risky. However, this might be considered for future calibrations of the model.

Greenhouse gas emissions

Although SOC in pastures and rangelands can be a C sink by improving grazing management, the practices involved also carry the risk of increasing GHG emissions (Henderson *et al*., 2015). Therefore, for better analysis and diagnosis, SOC balance should be addressed together with animal GHG emissions. This can be evidenced by the decline in C balance obtained by PastorC-Tambo when increasing forage production with high grazing use efficiency (65-85%), since the increase in GHG emissions offset the increase in SOC balance.

Greenhouse gas emissions increased linearly with stocking rate, regardless of the forage production levels or the grazing use efficiency. Despite the adjustment in digestibility included by selectivity under light and moderate use efficiency (adapted from Galli *et al*., 1999), there was a small effect in the whole system. This could be explained by a dilution of grazing DMI digestibility changes, as supplements had a moderate inclusion in the modal farm simulated. Conversely, Savian *et al*. (2018)

reported significantly higher reductions in absolute emissions and emission intensities with moderate stocking rates and a high residual sward height, which promotes pasture growth and thus forage production.

PastorC-Tambo GHG emissions estimations are restricted to enteric and fecal CH_4, as well as direct and indirect N_2O emissions from feces and urine. In this sense, total systems GHG emissions (including other sources) may be ever higher in intensified systems (i.e., high stocking rates) due to their heavy use of fossil fuels.

Carbon balance

Simulations with PastorC-Tambo yielded C balances between -2.54 and 0.64 t C/ha/year (-9.30 and 2.34 t CO_2 eq/ha/year), proving to be sensitive to changes in the main input variables as well as the importance of considering SOC balance mitigation capacity. Total mitigation was reached with medium and high forage production levels (18, 7 and 27 t DM/ha for alfalfa, oat and maize silage) together with light grazing (<45% grazing use efficiency). Although increases in stocking rate had low effect on SOC at constant forage productivity, animal GHG emissions grew proportionally, offsetting the mitigation capacity of soil C sequestration.

According to local estimations, alfalfa based pastures productivity under rain-fed conditions in the Pampas region averages 12 t DM/ha/year (Jauregui *et al*., 2022). This forage productivity, together with mean stocking rates of 1.46 cow/ha and supplementation rates of 288 g/l milk (Engler *et al*., 2022), would result in negative C balances between -0.5 and -1.0 t C/ha/year. However, around 50% of GHG mitigation would be achieved by C capture in soil under these conditions.

Viglizzo *et al*. (2019) suggested positive C balances for livestock production in South America. However, the model proposed by these authors was lacking adjustments from SOM mineralization (Villarino *et al*., 2020). Hence, C balances may have been overestimated. PastorC-Tambo not only considered soil mineralization but also mineralization coefficients that are sensitive to changes in SOC content and tillage systems. Nevertheless, mineralization rates are not adjusted by grazing use efficiency, which may have some impact on mineralization rates due to its effect on litter mass, root and microbial biomass, and soil temperature (Zhou *et al*., 2017). Due to the complexity of its inclusion and the lack of local information, this adjustment was not included in PastorC-Tambo.

Supplementation level

High supplementation improved C balance by enhancing SOC balance as well as reducing GHG emissions. This improvement could be explained by the increase in C returns to soil with the importation of supplements via feces (Whitehead *et al*., 2018). Furthermore, GHG emissions were reduced by the inclusion of highly digestible supplements, which is a widely recommended mitigation strategy that improves global digestibility of the diet and reduces ruminal methane yield (IPCC, 2019; Beauchemin *et al*., 2022).

Effluent treatment and milking time

Carbon balance differences between effluent treatment systems and milking time were not negligible, ranging from 0.019 to 0.426 t C/ha/year. This indicates that improved effluent and manure treatments represent a valuable mitigation strategy (Herrero *et al*., 2016; FAO and GDP, 2018). Increased milking time increases effluent production while reducing feces returning to soil during grazing (White *et al*., 2001). Efficient milking routines and well-designed facilities can reduce milking time and maximize time on grazing paddocks, especially considering that 19% of Argentine dairy farms have old abreast milking parlors (Engler *et al*., 2022).

Storage in uncovered anaerobic lagoons presented the highest methane emissions due to anaerobic conditions and the direct release to the atmosphere (Herrero, 2014; IPCC, 2019). The C balance improvement with the inclusion of solid separation and agronomic reuse, depended on the solid separation efficiency, which can widely vary (Gooch *et al*., 2005). Depending on the solid storage system used, it is possible to reduce methane emissions because manure decomposes under more aerobic conditions than lagoons (IPCC, 2019). The later agronomic use can increase C return to soil (Whitehead *et al*., 2018). On the other hand, anaerobic digestion allows the capture of methane generated and its use for energy supply (IPCC, 2019).

Manure reuse can increase soil C inputs and thus SOC balance. Whitehead *et al*. (2018) indicated that manure application can increase SOC at low but significant rates. However, further research and consideration are needed regarding N and P leaching and volatilization (Whitehead *et al*., 2018).

The daily spread of effluents needs special consideration. Despite the increase in C balance of this system compared with other systems, factors used from IPCC (2019) consider no lixiviation fraction and a very low volatile fraction, and this may have led to GHG emission underestimation. Moreover, daily spread may not be advisable since crude slurry application could lead to sanitarium concerns (Salgado *et al*., 2015).

Practical implications

Simulation models play a key role in research and outreach today. Greenhouse gas mitigation through C capture in pastures and rangelands soils, highlights the need of including it in farm scale models developed to estimate C balance and environmental sustainability of grazing dairy production systems (Viglizzo *et al*., 2019). The combination of some practices in order to improve forage production to promote C inputs to soil would allow a change from low to moderate intensification levels (i.e., stocking rates). However, high intensification levels are risky, since GHG emissions´ rise can offset the mitigation capacity of the soil (Soussana and Lemaire, 2014).

CONCLUSIONS

PastorC-Tambo is not aimed to predict the long term SOC content of dairy farms, but rather to assess the environmental status of commercial dairy production systems in a simple and practical way, including their mitigation capacity through soil C capture and sequestration. The use of PastorC-Tambo could lead to a rapid diagnosis of dairy farms´ status and promote changes in management and system design in order to mitigate undesirable impacts on the environment. Considering that taking action on climate change is urgent, this rapid assessment has a major value in the short term. Nevertheless, it should be combined with long term experiments to continuously adjust models, diagnoses, and mitigation strategies.

PastorC-Tambo is a simple model to estimate C balance of dairy production systems that proved to be sensitive to changes in pasture productivity, stocking rates, supplementation levels, and effluent treatments. This model could also be used for C balance evaluation under different land use rotation schemes and tillage systems. Furthermore, the use of PastorC-Tambo could contribute to the estimation of the environmental carrying capacity of commercial dairy farms in the Pampas region.

Pasture based dairy farms may act as a C source or sink to the atmosphere, contributing to or mitigating climate change. The mitigation capacity of these systems can be increased by enhancing pasture productivity, using moderate stocking rates, maximizing grazing time (and reducing confinement), improving effluent and manure treatment systems, and increasing C return to soil from manure. These variables depend directly on the daily farm management decisions, which makes PastorC-Tambo more useful as a tool to promote sustainable production.

APPENDIX: IPCC FACTORS AND COEFFICIENTS USED IN PASTORC-TAMBO

Methane production from enteric fermentation is estimated using the emissions factors reported in Table 10.12 from IPCC (2019).

Volatile solid excretion rates are estimated using equation 10.24 from IPCC (2019).

Methane emission factors from manure are taken from Table 10.14 from IPCC (2019):

- Pasture range and paddocks: 0.6 g CH_4/kg VS.
- Dry lot: Milking and dry cows: 1.3, 1.9 and 2.4 g CH_4/kg VS for low, medium and high productivity systems, respectively. Growing heifers and bulls: 1.55 g CH_4/kg VS.
- Uncovered anaerobic lagoon: 63.6, 90.5 and 117.4 g CH_4/kg VS for low, medium and high productivity systems, respectively.
- Solid separation and storage: 3.5, 5.0, 6.4 g CH_4/kg VS for low, medium and high productivity systems, respectively.
- Daily spread: 0.4, 0.6 and 0.8 g CH_4/kg VS for low, medium and high productivity systems, respectively.
- Anaerobic digestion - Biogas: 9.5, 6.6 and 3.7 g CH_4/kg VS for low, medium and high productivity systems, respectively.

N excretion is estimated from Tables 10.A1 and 10.A3 from IPCC (2019): 0.59 and 0.34 kg N/1000 kg live weight for milking cows and other categories, respectively.

Direct N_2O emissions factors are taken from Tables 10.21 and 11.1 from IPCC (2019):

- 0.006 kg N_20-N/kg N for pasture range and paddocks (Table 11.1 from IPCC, 2019).
- 0.02 kg N_20-N/kg N for dry lots, 0 kg N_20-N/kg N for uncovered anaerobic lagoons and daily spread, 0.005 kg N_20-N/kg N for solid separation and storage, and 0.0006 kg N_20-N/kg for anaerobic digestion- biogas (Table 10.21 from IPCC, 2019).

N volatilization and leaching fractions are taken from Tables 10.22 and 11.3 from IPCC (2019):

Volatilization fractions:

- 0.21 for pasture range and paddocks (Table 11.3 from IPCC, 2019).
- 0.30 for dry lots, solid separation and storage and anaerobic digestion – biogas, 0.35 for uncovered anaerobic lagoons, and 0.07 for daily spread (Table 10.22 from IPCC, 2019).

Leaching fractions:

- 0.24 for pasture range and paddocks (Table 11.3 from IPCC, 2019).
- 0.035 for dry lots, 0 for uncovered anaerobic lagoons, daily spread and anaerobic digestion – biogas, and 0.02 for solid separation and storage (Table 10.22 from IPCC, 2019).

Indirect N_2O emissions factors are taken from Table 11.3 from IPCC (2019):

- 0.014 kg N_20-N/kg N volatilized.
- 0.011 kg N_20-N/kg N leached.

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