CARBON FLUX ASSESSEMENT IN COW-CALF GRAZING SYSTEMS

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Introduction

GHG fluxes from grasslands ecosystems are intimately linked to grazing management. In grasslands, CO_2 is exchanged with the soil and vegetation, N_2O is emitted by soils and CH_4 is emitted by animals and exchanged with the soil. When CO_2 exchange with vegetation is included on net GHG exchange calculation, these ecosystems are usually considered GHG sinks (Soussana et al, 2007; Allard et al., 2007). Similarly, the inclusion of SOC change in net GHG exchange accounting might result in grasslands with GHG sink potentials (Liebig et al., 2010).

Grasslands management choices to reduce GHG budget may involve important trade-offs. Allard et al. (2007) and Soussana et al. (2007) studied net GHG exchange from grasslands including CO_2 exchange with the vegetation, and observed net CO_2 equivalent sink activity, but with different trade-offs. Allard et al. (2007) observed that enteric CH_4 emissions expressed as CO_2 equivalent strongly affected GHG budget in intensive and extensive managed grasslands (average 70% offset of total CO_2 sink activity). Soussana et al., (2007) observed that addition of enteric CH_4 and N_2O emissions from pasture soils to CO_2 sink activity of grasslands resulted in relatively small offset of total CO_2 sink activity (19% average). The small trade-off observed by Soussana et al. (2007) was not enough to affect the CO_2 equivalent sink potential of the sites studied.

Management of grasslands modifies SOC storage (Conant et al., 2001; Schuman et al., 2002), potentially increasing C sequestration (Follet et al., 2001). Grasslands management primarily affects SOC storage by modifying C inputs to the soil, including root turnover and C allocation between roots and shoots (Ogle et al., 2004). Liebig et al. (2010) suggested that the factors contributing to net GHG exchange decreased in relative impact in the order of SOC change, soil-atmosphere N_2O flux, enteric CH_4 emissions, CO_2 emissions associated with N fertilizer production and application, and soil-atmosphere CH_4 flux. Similarly, Roberston et al. (2000) observed that SOC change and N_2O flux control net GHG exchange in agroecosystems.

In this study we assessed the net GHG exchange (in terms of Ceq flux) of 2 grazing systems differing in stocking rate and density. We hypothesized that low stocking rate, high stocking density systems have lower C flux resulting from less animals per area, and higher accumulation of SOC because of longer rest periods.

Material and Methods

Pasture management and GHG collection

Cow-calf pairs were managed with 2 rotational grazing management practices differing in stocking rates and density; an intensive system with high stocking rate and low stocking density, and an extensive system with low stocking rate and high stocking density. The system with low stocking rate and high stocking density (SysA) consisted of 120 cow-calf pairs rotating on a total of 120 ha, divided into 0.7 ha paddocks. Cow-calf pairs were moved to a new paddock 3 times daily (at approximately 0600 h, 1200 h and 1800 h). The equivalent stocking rate was 1 cow ha^{-1} and the stocking density was approximately 100,000 kg LW ha^{-1}. The rest period varied from 60 to 90 d during the course of the growing season depending on plant growth. Cow-calf pairs grazed each paddocks 2 to 3 times per year. The system with high stocking rate and low stocking density (SysB) consisted of 4 cow-calf pairs rotating on 1.6 ha pasture, divided into 0.08 ha paddocks. Cow-calf pairs were moved to a new paddock once daily (at approximately 0800 h). The equivalent stocking rate was 2.5 cows ha^{-1} and the stocking density was 28,000 kg LW ha^{-1}. The rest period varied from 18 to 30 d during the course of the growing season depending on plant growth. Cow-calf pairs grazed each paddocks 4 to 5 times per year. The pasture sites in SysB were irrigated as needed, whereas there was no irrigation applied to SysA pasture sites. The only fertilization application was on SysB pasture sites that received urea fertilization (23 kg of actual urea) on June 3rd of 2011 (approximately 30 d before the start of gas sampling, see dates below). In addition to these 2 systems, grazing-exclusion pasture sites (GE) were monitored in order to account for GHG emissions from non-grazed pastures. The use of a non-grazed pasture site was important to confirm that any differences found between SysA and SysB were attributed to the grazing management practices implemented. The soil type across treatments pasture sites was predominantly sandy loam.

SysA and SysB areas were sampled during 3 years (2011 to 2013). Sampling for all treatments was repeated in 2 periods; at the beginning of the grazing season (period 1 – P1) and at the end of the grazing season (period 2 – P2). The first year was considered a preliminary year, for the purpose of adjusting the methodology for GHG from soils collection. For that reason, GE pasture sites were not sampled, dates of periods monitored were closer together in time as compared to 2012 and 2013, soil bulk density (BD) was not monitored, soil was sampled to 10 cm depth, and enteric CH_4 emissions were not monitored. For details on dates of each period and methodologies used on GHG emissions from soils and enteric CH_4 emissions refer to Chapter 2, section 2.2 and Chapter 3, section 3.2. Soil texture and pH in each treatment are described in Table 2.1, Chapter 2.

Soil sample collection occurred in paddocks most recently occupied by cows. Soil samples were collected from 0.08 ha paddocks (3 pseudoreplicates per treatment). Soil sampling occurred approximately 20 days post-grazing. The sampling dates were: August 1st, and August 28th, 2011; June 3rd and September 15th, 2012; June 30th and September 28th, 2013.

Soil bulk density determination

Soil BD samples were collected with a 7.6 cm diameter and 7.5 cm height brass ring, avoiding disturbance of soil structure. Samples were weighed, dried at 105°C to constant weight, and re-weighed. Bulk density was calculated by dividing the dry weight by the soil core volume (Blake and Hartge, 1986). Soil BD was not assessed during 2011. Soil BD was monitored in different depths to allow SOC stock calculation (described below). However the distinction of BD at the 0 to 5 cm and 5 to 10 cm depths was not possible because of the ring height (7.5 cm). For that reason, BD in the top soil was assessed from 0 to 7.5 cm and it was used to calculate SOC stock at 0 to 5 cm and 5 to 10 cm depths. SOC stock at 10 to 20 cm was calculated with BD of 10 to 17.5 cm depth, and SOC stock at 20 to 30 cm was calculated with 20 to 27.5 cm BD.

4.2.3. Soil organic matter and C and N stocks determination

During 2012 and 2013, the soil pool was assessed at different depths: 0 to 5 cm, 5 to 10 cm, 10 to 20 cm, and 20 to 30 cm. SOC and TSN stocks were not monitored during 2011. A 0 to 30 cm depth is often used to report C stocks in soils (Schipper and Sparling, 2011). Previous studies suggest that changes in soil C and N can extend throughout the soil profile rather than just in the topsoil (Schipper et al., 2007; Franzluebbers and Stuedemann, 2009). Therefore, sampling occurred at different depths to illustrate changes along the profile and address the concern that changes in the surface soil may not represent storage in deeper horizons (Blanco-Canqui and Lal, 2008). For each replicate (0.08 ha paddock) 10 soil samples were randomly collected at each depth and composited per paddock. Soil samples were dried at 65°C separated in 2 sub samples. One sub sample was sent to the Michigan State University Soil and Plant Nutrient Laboratory for SOM determination. SOM was determined by wet digestion and colorimetry (Schulte and Hopkins, 1996). The second sub sample was ground manually with a pestle and mortar and sent to Michigan State University Great Lakes Bioenergy Research Center Laboratory for analysis of C and N.

Soil OC and total soil N (TSN) from soil samples were determined by an Elemental Combustion System (ECS 4010 CHNSO Analyzer, Costech, Valencia, CA). The ECS uses combustion and gas chromatography with thermal conductivity detector and helium as carrier gas to determine N_2 and CO_2. We tested for the presence of inorganic C in the soils of the study area and concluded that no inorganic forms were present, thus total C represents SOC. Carbon: nitrogen ratio was calculated for 0 to 30 cm depths.

Soil OC and TSN stocks were calculated based on soil layers of fixed depth (Equation 4.1). However, given that we observed high variability on BD between years and among treatments, we corrected SOC and TSN values for a fixed mass of soil, as suggested by Ellert et al. (2002; Equation 4.2 to 4.4 use SOC as example of calculations). This approach includes the selection of a reference soil mass (M_{ref}), which is the lowest soil mass to the prescribed depth from all sampling sites. The M_{ref} is then used to determine the soil mass to be subtracted from the deepest core segment (excess mass of soil: M_{ex}) so that mass of soil is equivalent to all sampling sites

Equation 4.1. Soil organic carbon and nitrogen stock calculated based on soil layers of fixed volume.

$$SOC_{FD} = \Sigma\ C_i \times BD_i \times L_i \times 0.1$$

where SOC_{FD} is SOC stock to fixed depth (Mg ha^{-1}), C_i is organic carbon concentration in depth i (mg C g^{-1} dry soil), BD_i is the bulk density of soil in depth i (g m^{-3}), and L_i is the length of the depth i (cm).

Equation 4.2. Determination of soil mass in each depth.

$$M_{soil} = \Sigma\, BD_i \times L_i \times 100$$

where M_{soil} is mass of soil to a fixed depth (Mg ha^{-1}), BD_i is bulk density of soil in depth *i* (g/m^3), and L_i is the length of the depth *i* (cm).

Equation 4.3. Determination of mass of excess soil in each depth.

$$M_{ex} = M_{soil} - M_{ref}$$

where M_{ex} is mass of excess soil (Mg ha^{-1}), M_{soil} is the mass of soil to a fixed depth (Mg ha^{-1}), and M_{ref} is the lowest soil mass selected from all sampling sites and depths (Mg ha^{-1}).

Equation 4.4. Determination of SOC stock to fixed mass of soil.

$$SOC_{FM} = SOC_{FD} – M_{ex} \times C_{dl}/1000$$

where SOC_{FM} is the SOC stock for a fixed mass of M_{ref}, M_{ex} is mass of excess soil (Mg ha^{-1}), and C_{dl} is organic carbon concentration in the deepest depth (mg C g^{-1} dry soil).

4.2.4. C flux calculations

In this study, fluxes from the ecosystem to the atmosphere are considered a contribution to the atmosphere budget. Therefore, positive GHG emissions indicate emissions to the atmosphere and negative GHG emissions indicate sink activity. According to Chapin et al. (2002) and adapted later by Soussana et al., (2007) the net GHG exchange (NGHGE) of a managed grassland ecosystem is calculated as:

$$NGHGE = NEE + F_{CH4} + F_{N2O}$$

where NEE is the net ecosystem exchange of CO_2 that includes emissions from soil and plant respiration, F_{CH4} is the CH_4 flux from soil and F_{N2O} is N_2O flux from the soil. We adapted the calculation to obtain the net GHG exchange in terms of C equivalent (Ceq_{flux}). The Ceq_{flux} for each site was calculated by adding CH_4 and N_2O emissions to CO_2 emissions using the global warming potential of each of these gases at the 100-year time horizon (IPCC, 2007; GWP_{N_2O} = 298 and GWP_{CH4} = 25), as follows

$$Ceq_{flux} = F_{CO2} + F_{CH4soil} + F_{N2O} + F_{CH4cows}$$

where F_{CO2} is the C equivalent flux of CO_2 from the soil, $F_{CH4soil}$ is the C equivalent flux of CH_4 from the soil, $F_{CH4cows}$ is the C equivalent flux of enteric CH_4 from the cows, and F_{N2O} is the C equivalent flux of N_2O from the soil. In contrast to Soussana et al. (2007) our F_{CO2} does not include CO_2 lost by plant and animal respiration. The largest part of organic C ingested during grazing is highly digestible and is respired shortly after intake (Soussana et al., 2007). Additional C loss (5% of digestible C) occurs through enteric CH_4 emissions, which was accounted for by the term $F_{CH4cows}$. We did not account for enteric CH_4 from the calves. The non-digestible C (from 25 to 40% of the intake depending on herbage digestibility) is returned to the pasture mainly as feces (Soussana et al., 2007). We did not differentiate between manure-derived emissions and soil-derived emissions. Soil emissions sampling was post-grazing and hence we assume that any emissions from feces or urine decomposition is accounted for in the soil term.

Soussana et al. (2007) and Chapin et al. (2002) included the C lost from the system through plant biomass export. Because our calculations are limited to the grazing season we assumed no C loss via herbage cutting and removal from the sampled sites. C loss from herbage decomposition on top of the soil is assumed to be included in CO_2 and CH_4 emissions from the soil, SOM and SOC content. There was no addition of C into our systems by organic fertilization and hence it is not included on the calculations. We did not account for C leaching from pasture soils.

In order to allow summation of GHG fluxes from soil and cows and determination of Ceq_{flux}, $F_{CH4cows}$ (originally in g CH_4 cow day^{-1}) was converted to an area basis (g CH_4 ha d^{-1}), using stocking rates of each system: SysA = 1 cow ha^{-1}, and SysB = 2.5 cows ha^{-1}. We monitored only the grazing season and the Ceq_{flux} is shown as daily average flux, because extrapolation to annual flux would be inaccurate.

SOC stock change was not included in the Ceq_{flux} determination because SOC content was monitored for a period of 2 years, which is not considered long enough to detect accurate SOC changes (Schuman et al., 2002). However, we consider SOC stock in our discussion of Ceq_{flux} because the main objective of this study was to show the importance of looking at different pools when assessing GHG emissions from grazing systems. SOC stock is an important pool to consider in any C flux accounting.

4.2.5. Statistical analysis

SOC and TSN stocks data were analyzed as a completely randomized design. Statistical analyses were performed using SAS Software (Version 9.2; SAS Institute, 1987). Paddocks were considered experimental units and were treated as the random term, and the compressed term year × period was considered a repeated measure. We associated the effects of year and period to the variability of the data, and hence means are shown pooled my year and period. The main reason for showing pooled means was that the length of this study was not long enough to allow assessment of SOC change in time, and showing means by year could lead to inaccurate conclusions. All tests were performed with 95% confidence ($\alpha = 0.05$). Soil and animal GHG emissions data were analyzed as described in Chapter 2, Section 2.3.3 and Chapter 3, Section 3.2.3, respectively.

Ceq_{flux} data were analyzed as a completely randomized design. Paddocks were considered experimental units and were treated as the random term, and the compressed term year × period was considered a repeated measure. When the main effect of year was significant differences were discussed separately by year. When the main effects of treatment or period were significant the interaction treatment × period was evaluated and pre-planned comparisons within treatment and period were performed. All tests were performed with 95% confidence ($\alpha = 0.05$).

Results and Discussion

Soil characteristics

Soil sampling was performed in different pasture sites during each year and period sampled, depending on animal management. The sampling sites in GE were maintained constant for all sampling occasions. A summary of particle size fractions in each pasture size is described in Table 2.1, Chapter 2.

Soil BD values were different from 2012 to 2013 ($P < 0.01$), but did not change from P1 to P2 ($P = 0.19$). Therefore means are poled by period. Soil BD increased with soil depth but no treatment effects were observed (Table 4.1). The accumulation of litter over time is a result of rotational grazing, with adequate rest periods for regrowth. The presence of organic litter dissipates the animal trampling impact, resulting in less compaction and lower soil BD of the soil (Sanjari et al., 2008). The accumulation of litter protected grazed soils from compaction, resulting in no BD differences between grazing systems and GE. Savadogo et al. (2007) and Franzluebbers and Stuedemann (2009) reported BD values similar to this study.

Soil BD has been found to increase because of grazing in soils with large quantities of fine soil particles (clay + silt) that are more sensitive to animal traffic and compaction (Vanhaveren, 1983; Abdelmagid et al., 1987). Our pasture sites were predominantly comprised of sand particles, and mostly sandy loam.

4.3.2. SOC and TSN stock and SOM content

We observed year and period effects on SOC stocks ($P < 0.01$ and $P = 0.05$, respectively), which are likely associated to spatial and temporal variability. Soil C stocks display high spatial variability, especially in grasslands. Cannell et al. (1999) found a coefficient of variation of 50% when evaluating spatial variability of C stocks in grasslands as compared to 15% in arable lands. Previous research have associated the variability to sampling at different depths (Bird et al., 2002), climate (Conant et al., 2001), texture (mainly clay content; Parton et al., 1987), and lack of evaluation of C distribution within the grazing system (Schumann et al., 1999). The ability to detect change in SOC stocks depends on the time since the original sampling, spatial homogeneity of the soil and intensity of sampling (Schipper et al., 2010). In this study, sampled paddocks (pseudoreplicates) were different at each year and period (see Section 4.2.), which did not allow spatial homogeneity between soil samples. In addition, Conant et al. (2001) suggested that periods of 5 to 10 years for a field scale study would be adequate to detect changes in SOC stock. Therefore, the change observed from 2012 to 2013 cannot be associated to SOC stock change (i.e. accumulation or loss). However, because the studied grazing systems were implemented at the study site for 5 years prior to 2012, the relative change between treatments may be considered.

Table 4.2 illustrates SOC stock means by treatment pooled by year and period. On average, SOC stock was higher for SysB pasture sites, and the difference between GE and SysA was not significant (63, 42 and 47.4 Mg C ha^{-1} for SysB, GE and SysA respectively, $P < 0.01$). In SOM, N and C are predominantly covalently bonded (Schipper et al., 2010) and thus the pattern of TSN accumulation in pasture sites was highly correlated to SOC accumulation (Table 4.2). SysB pasture sites had higher TSN stocks compared to GE and SysA (4.85, 3.44 and 3.95 Mg N ha^{-1}, for SysB, GE and SysA respectively, $P < 0.01$). A similar relationship between C and N reported by Pineiro et al. (2009).

The effects of grazing management on C cycling and distribution has been evaluated before, however, literature does not yet suggest a clear relationship between grazing management and C sequestration. Some studies have reported no effect of grazing on SOC stock (e.g. Milchunas and Laurenroth, 1993), others reported increases (Weinhold et al., 2001) or a decrease (Derner et al., 1997). Differences in findings between SOC stocks and grazing management has been associated with factors that affect C cycling and sequestration potential on grasslands, such as: climate, inherent soil properties, landscape position, plant community composition, and grazing management practices (Reeder and Schuman, 2002). The management applied to the land affects soil's ability to retain organic C. Practices that increase plant productivity and C inputs to the soil, and decrease soil exposure to sunlight and erosion allow greater C accumulation (Parton et al., 1987).

Reeder and Schuman (2002) studied the impact of heavy or light grazing on SOC stocks, compared to non-grazed areas. In their evaluation of the 0 to 30 cm layer, they observed significantly higher SOC stock in grazed pastures (67 Mg C ha^{-1}) compared to non-grazed pastures (58 Mg C ha^{-1}). The range of SOC stock observed was from 55 Mg C ha^{-1} to 100 Mg C ha^{-1}. We observed wider range of SOC stock values among all treatments (from 25 to 113 Mg C ha^{-1}; data not shown). The greater variability observed in this study might be associated to the sampling in different pasture sites at each year and period. Sanjari et al. (2008) observed lower SOC stock values for rotational grazing, continuous grazing and non-grazed pasture sites in 5 years of monitoring (on average 25 Mg C ha^{-1}). However, increased SOC content in rotational grazing pasture sites compared to continuous grazing or non-grazed pasture sites was observed by Sanjari et al. (2008) and associated to greater grass growth and rest periods. Southorn (2002) attributed the greater SOC accumulation in rotational grazing systems to the larger proportion of plant material being incorporated into the soil. In addition, adequate rest periods is a key driver in the recovery of grazed species and increase in aboveground organic material, followed by its subsequent incorporation into the soil, resulting in increased SOC (Gillen et al., 1991).

In this study, SysA pasture sites were given longer rest periods (60 to 90 d) than SysB pasture sites (18 to 30 d). Nevertheless, the increased SOC stock of SysB pasture sites suggested that grazing management of SysB is increasing SOC stocks at a faster rate than SysA or GE ($P < 0.01$; Table 4.2). Naeth et al. (1991) suggested that grazing, such as that in SysB, reduces litter mass accumulation because animal traffic enhances physical breakdown and incorporation of litter into the soil. It is likely that more frequent grazing in SysB reduced litter accumulation, and enhanced physical breakdown increasing litter decomposition and incorporation into the soil. Frequent grazing also could have stimulated forage and roots development, increased soil water content and microbial development, enhancing the rate of decomposition of litter and transfer of C into deeper layers of the soil (Sharif et al., 1994). Root decay, although not measured in this study, was identified as another reason for increased SOC under rotational grazing systems. Intensive defoliation under a single grazing event results in cessation of plant respiration, leading to death of roots within a few hours after grazing, in order to equalize biomass (Sanjari et al., 2008). In SysB defoliation was intensive and more frequent than in SysA.

In SysA, forage offered to cow-calf pairs was mature and in reproductive stage, which resulted in selective grazing by cows for higher quality plants (see discussion on Chapter 3, Section 3.3.3). Forage that was not ingested was trampled down, resulting in greater litter accumulation on soil surface (Table 3.1, Chapter 3). The significantly lower SOC stock in SysA and GE compared to SysB might be the result of immobilization of C in excessive aboveground plant litter, due to longer rest periods (SysA) or non-grazing (GE).

Soil organic C constitutes approximately 60% of SOM (Bardgett et al., 2009). Consequently, the differences in SOM content between treatments were similar to the differences observed for SOC stocks. SysB had higher SOM content to 30 cm than SysA or GE that did not differ (4.07%, 3.33% and 3.22%, for SysB, SysA and GE, respectively, $P < 0.01$). SOM decreased throughout the soil profile in all treatments (Figure 4.1).

In SysA pasture sites, animal trampling was more intense at each grazing occasion (due to higher stocking density), but it was less frequent (longer rest periods). The higher stocking density might have contributed to the formation of litter on soil surface, but without frequent animal trampling, it is likely that litter decomposition happened at a slow rate. Because of higher stocking density, cow-calf pairs grazed each paddock of SysA for a short period of time (8 to 12 h). The short time of grazing was likely not prolonged enough to accelerate litter decomposition and incorporation into the soil. Reeder and Schuman (2002) suggests that a build-up of litter on the soil surface affects soil temperature and soil water content, which will, in turn, affect plant residue and SOM decomposition rates.

When observing the SOC distribution along the soil profile, SysB contained higher SOC content in the 20 to 30 cm layers compared with SysA ($P = 0.02$) and GE ($P = 0.03$; Figure 4.2). It was interesting to find that SysB pasture sites had accumulated C mainly in deeper layers. We expected that, because of the long rest period and lack of irrigation on SysA, deep-rooted plant species would develop and significantly contribute to SOC accumulation in deeper layers, as it was observed before (Fisher et al., 1994). However, botanical composition did not support that hypothesis (Table 3.2, Chapter 3). Legumes were found to be present on both SysA and SysB pasture sites, and the same grasses species were found on both systems (although on different proportions).

The surface depth (0 to 10 cm) generally contains the highest levels of labile C, indicative of rapid turnover. This labile C is important mainly to ecosystem function and microbial development. It represents the C participating in C cycling within the ecosystem and is not representative of sequestered C. Carbon sequestered in deeper layers, indicates favorable conditions for root penetration and high levels of microbial activity. Deeply sequestered C enhances ecosystem hydrology and nutrient recycling. Additionally sequestration of C on deeper layers provide long-term benefits, because C is less susceptible to loss from surface-soil disturbances (Franzluebbers and Stuedemann, 2009). Our data supports earlier findings that change in soil C can extend throughout the soil profile (Schipper et al., 2010; Schipper et al., 2007). Schipper et al. (2010) observed that despite the apparent long residence time of soil C in deep horizons, SOC moves through 1 m-deep horizons more rapidly than previously thought. The frequent trampling effect caused by the cow-calf pairs in SysB resulted in disruption of surface soil crust and soil aggregates, increasing SOM decomposition and SOC incorporation in deeper depths (Liu et al., 2004; Neff et al., 2005). Intensive grazing has been associated to high rate of SOM decomposition (Sanjari et al., 2008).

TSN concentration was also highly stratified with depth and followed SOC accumulation (Figure 4.3). Conant et al. (2005) and Franzluebbers and Stuedemann (2009) find that changes in SOC stock were closely related to changes in TSN stock. There are potential benefits as a result of coupling between soil C and N changes. For example, the sequestration or loss of 1 Mg C is associated with approximately 100 kg of N gained or lost (Schipper et al., 2010). There was no treatment effect on C:N ratio (Table 4.2). The relatively high C:N ratio observed in this study suggest that C and N immobilization is the dominant processes over mineralization (Du Preez and Snyman, 1993).

Total C equivalent flux

Means are shown separately by year and period for F_{CO2}, $F_{CH4soil}$, F_{N2O}, $F_{CH4cows}$ and Ceq_{flux} (year effect $P < 0.01$; Table 4.3). Daily means are presented in order to allow discussion on the overall Ceq_{flux} between grazing systems and non-grazed pasture sites (Table 4.4).

Grazing systems versus non-grazed pasture sites - Generally, grazing systems had higher Ceq_{flux} than GE pasture sites, except during P2 of 2012, when the difference between SysA and GE was not significant (Table 4.3). The increased Ceq_{flux} from grazing systems was expected because $F_{CH4cows}$ was considered zero for GE. However, the difference between grazing systems and GE was substantially small.

The initial hypothesis was that Ceq_{flux} would be increased in grazing systems not only due to enteric CH_4, but also because of manure decomposition in pasture soils. However, during 2012 the difference between grazing systems and GE was approximately 3 kg C ha d^{-1}, which approximates $F_{CH4cows}$. This suggests that during 2012, grazing did not increase GHG flux from the soil. The Ceq_{flux} pooled by treatment during 2012 (average 10.3 kg C ha d^{-1}) was greater when compared to 2011 (9.6 kg C ha d^{-1}) and 2013 (19.8 kg C ha d^{-1}). The year of 2012 was relatively dry, with precipitation concentrated in a few days during the grazing season (Table 2.1, Chapter 2). The low soil moisture content could have decreased GHG flux from the soil in all pasture sites. The year of 2011 does not include $F_{CH4cows}$.

During 2013, the difference in Ceq_{flux} between grazing systems and GE was greater (approximately 8 kg C ha d^{-1} during P1, and 11 kg C ha d^{-1} during P2) than the contribution of

$F_{CH4cows}$ (on average 3.3 kg C ha d^{-1}). Generally, during 2013 GE pasture soils had decreased F_{CO2}, $F_{CH4soil}$, and F_{N2O} compared to grazing systems. GE pasture sites were the only ones with observed N_2O and CH_4 sink activities, during the 2013 grazing season. The higher levels of moisture in the soil (compared to 2012) likely increased microbial activity, resulting in increased GHG exchange from pasture soils. During P2 of 2013, SysB had greater Ceq_{flux} than SysA and GE. It was the only occasion when the difference between grazing systems was observed.

SysA versus SysB

During 2011, $F_{CH4cows}$ was not monitored and Ceq_{flux} represents the addition of F_{CO2}, $F_{CH4soil}$ and F_{N2O} (Table 4.3). F_{N2O} and $F_{CH4soil}$ were not different between treatments in neither period. During P2, SysB had greater F_{CO2} than SysA (7.64 and 6.07 kg C ha^{-1} d^{-1}, respectively), which resulted in greater Ceq_{flux} from SysB pasture sites than SysA during P2. Pooled by treatment, Ceq_{flux} decreased considerably from P1 to P2 (11.2 and 8.2 kg C ha^{-1} d^{-}1, for P1 and P2, respectively; $P < 0.01$). Because there were no consistent differences in F_{N2O} and $F_{CH4soil}$ from P1 to P2, the decrease in Ceq_{flux} is due only to the decrease in F_{CO2}. These results suggest that, when $F_{CH4cows}$ is not taken into account, F_{CO2} seems to be the driver of Ceq_{flux} in grazed pastures.

During 2012, $F_{CH4cows}$ is included in Ceq_{flux}. The differences between systems observed in F_{CO2}, $F_{CH4soil,}$ F_{N2O}, or $F_{CH4cows}$ were not significant, and consequently the difference between systems in Ceq_{flux} was likewise not significant (Table 4.3). Despite the greater stocking rate of SysB (2.5 cows ha^{-1}) compared to SysA (1 cow ha^{-1}), $F_{CH4cows}$ were not significantly different between grazing systems during P2. We expected greater $F_{CH4cows}$ from SysB because of the greater number of cows per hectare. However, the results suggest that SysA cows had relatively high enteric CH_4 emissions, during 2012 (Table 4.3)

During 2013, SysB had higher Ceq_{flux} when compared to SysA during P2 (22.49 versus 13.40 kg C ha^{-1} d^{-1}, respectively; $P < 0.01$). The increased Ceq_{flux} from SysB was a result of greater $F_{CH4cows}$ compared to SysA during P2 (6.22 versus 1.61 kg C ha^{-1} d^{-1}, respectively; $P = 0.02$), because SysB did not have increased GHG emissions from soils compared to SysA (Table 4.3). During P1, again SysB had greater $F_{CH4cows}$ compared to SysA (3.26 versus 1.93 kg C ha^{-1} d^{-1}, respectively $P = 0.03$). However, Ceq_{flux} was not different between grazing systems (24.11 and 23.35 for SysA and SysB, respectively, $P = 0.13$). The decreased $F_{CH4cows}$ in SysA, was offset by the numerical increased F_{N2O}, which increased Ceq_{flux} of SysA. These results suggest that the contribution of enteric CH_4 to Ceq_{flux} may be not always be the driver of higher GHG emissions. Robertson et al. (2000) showed that half of the total net CO_2 equivalent emissions from arable sites was contributed by N_2O production. Our results indicate that under specific circumstances this concept might apply to grasslands. Results from Soussana et al. (2007) indicate that despite the large error in enteric CH_4 measuring, the CH_4 emission rate would not lead to a large change in the net GHG exchange of the studied grasslands.

Daily Ceq_{flux} pooled by year and period

In order to allow the comparison between treatments across years and periods, we pooled daily means (Table 4.4). It is important to keep in mind that we sampled only during the grazing season. By not monitoring Ceq_{flux} during the winter, early spring or late fall, the pooled daily means cannot be extrapolated to annual means.

Daily Ceq_{flux} from grazing systems was higher than non-grazed pasture sites by approximately 5.8 kg C ha^{-1} d^{-1} ($P < 0.01$). The largest contributor for the greater Ceq_{flux} from grazing systems compared to GE was $F_{CH4cows}$. However, pooled across years grazing systems also had higher F_{N2O} and $F_{CH4soil}$ than GE. Between grazing systems the difference in Ceq_{flux} ($P = 0.60$) was not significant. The only flux that was different between grazing system was $F_{CH4cows;}$ SysB had greater $F_{CH4cows}$ than SysA (4.91 versus 2.09 kg C ha^{-1} d^{-1}, respectively; $P < 0.01$). The increased $F_{CH4cows}$ from SysB was a consequence of higher stocking rate, because daily enteric CH_4 emissions were not difference between systems across years (Table 3.5, Chapter 3). The contribution of $F_{CH4cows}$ in SysB was not large enough to increase Ceq_{flux}.

Typical N_2O emissions from grasslands soils converted into C equivalent range between 0.3 and 3 kg C ha^{-1} d^{-1} (Machefert et al., 2002). Freibauer et al. (2004) observed N_2O fluxes of 0.7 kg C ha^{-1} d^{-1} from grasslands. On the other hand, Soussana et al. (2007) studied grasslands GHG flux throughout the year and found N_2O emissions varying from -0.08 to 2.4 kg C ha^{-1} d^{-1}. In the present study, we observed F_{N2O} from 0.06 to 1.35 kg C ha^{-1} d^{-1}.

Regarding $F_{CH4soil}$, we observed sink activity ($F_{CH4soil}$ range was from -0.16 to 0.14 kg C ha^{-1} d^{-1}, whilst Soussana et al. (2007) when monitoring CH_4 fluxes throughout the year obtained higher emissions (0.2 to 1.3 kg C ha^{-1} d^{-1}). They associated the lower sink activity observed to the presence of grazers, suggesting that grazing reduces the on-site sink activity for CH_4. In fact, the negative mean of $F_{CH4soil}$ in the present study was from GE pasture sites (Table 4.3). Deposition of excreta by animals is expected to produce CH_4 emissions at a very low level (as compared to application of organic fertilizers; Jarvis et al., 2001), but may increase N_2O emissions (Smith et al., 2001).

In the present study, very low $F_{CH4soil}$ was observed and when differences between treatments were observed they were due to F_{CO2}, F_{N2O} or $F_{CH4cows}$ (Table 4.3). Liebig et al. (2010) suggested that factors contributing to net GHG exchange in grasslands were decreased in relative impact order of SOC change, soil-atmosphere N_2O flux, enteric CH_4 emissions and soil-atmosphere CH_4 flux.

We did not include SOC change in Ceq_{flux} determination, and the differences in N_2O fluxes were not significant between grazing treatments, which resulted Ceq_{flux} differences that were not significant between grazing systems. Liebig et al. (2010) including SOC change in the GHG exchange determination, observed negative net GHG from heavily and moderately grazed grasslands. Allard et al. (2007) and Soussana et al. (2007) also observed negative GHG exchange from grasslands, because CO_2 exchange with the vegetation was included on the determination of net GHG exchange. The annual mean Ceq_{flux} from SysB was lower than the annual mean Ceq_{flux} from SysA (Table 4.4), although means were not statistically different. However, if SOC change was included on Ceq_{flux} these results and conclusions could change. SOC stock results suggested that potentially SysB is accumulating higher SOC than SysA (Table 4.2), but long-term monitoring of SOC stock in the study is needed to allow incorporation of SOC change in Ceq_{flux} determination.

Generally, the higher stocking rate in SysB increased $F_{CH4cows}$, but did not affect $F_{CH4soil}$ and F_{N2O}. We believe that the lower stocking density in SysB and irrigation allowed shorter rest periods, frequent herbage defoliation, faster return of nutrients to soils from excreta deposition, increased plant growth and roots development. These factors, in addition to greater TSN content in SysB, might have contributed to microbial development and faster nutrient cycling, decreasing GHG emissions from soils. It was demonstrated in Section 4.3.2 that SysB is potentially increasing SOC stocks at a faster rate than SysA or GE. Similarly, SOM content was higher in SysB compared to SysA and GE, which suggests faster litter decomposition. SOC accumulation on deeper layers (20 to 30 cm) was greater in SysB, which also suggests potential of C sequestration. In addition, SysB gives the producer more flexibility in terms of animal production. Because of shorter rest periods and frequent defoliation forage quality remained high and constant throughout the grazing season (Table 3.3, Chapter 3). The maintenance of forage quality permits the production of different types of animals, such as finishing steers for instance, which permits the producers to aggregate value to their final product according to market changes.

In SysA there was a decrease in forage quality from P1 to P2 (Table 3.3, Chapter 3) but $F_{CH4cows}$ was not increased, which was associated to selective grazing. We observed the development of legumes in both systems, indicating that the grazing management is not depleting the development of specific plant species, and selective grazing is allowed in both systems. SysA does not need irrigation and longer rest periods results in litter accumulation on the top soil, with slow decomposition rate. It is possible that the SOM slower decomposition rate of SOM in SysA could provide greater resilience to SysA compared to SysB.

It is important to remember that we monitored GHG exchange during the grazing season only. We did not account for emissions in other periods other than post-grazing, and hence annual emissions may not be accurate. Similarly, we are assuming that the grazing seasons of both systems were of the same duration. If one system allowed prolonged or shortened grazing season, Ceq_{flux} would change.

4.4. Conclusion

Grazing systems had greater Ceq_{flux} than non-grazed pasture sites. The largest contributor to increased Ceq_{flux} from grazing systems was enteric CH_4 emissions. However, on an annual basis, grazing systems also had increased N_2O and CH_4 emissions from pasture soils, compared to non-grazed pasture sites. Non-grazed pasture sites were the only sites with CH_4 sink activity. The effect of greater enteric CH_4 contribution from SysB, due to higher stocking rate than SysA, was offset by GHG exchange from the soil. Hence, our results indicate no clear difference in C equivalent flux between the grazing systems studied, when SOC change is not incorporated. SysB potentially increased total SOC stock, the addition of SOC to deeper into the soil horizon and SOM content to 30 cm. SysA, with longer rest periods, allowed litter accumulation on the top soil, resulting in slower SOM decomposition rate, which can result in greater resilience in the long-term.

Grazing management should be adaptive and farm decisions are inherent to grazing management. Both SysA and SysB have opportunities to improve ecosystems services at the farm level, including animal production and food provisioning. Long-term research is needed to confirm SOC stock and SOM decomposition rates of these systems. The incorporation of C sequestration into the determination of Ceq_{flux} could change results and possibly differentiate the grazing systems studied.

Table 4.1. Soil bulk density in pasture soils grazed under two management strategies and non-grazed.

Soil depth, cm	Systems[1]		
	GE	SysA	SysB
2012 grazing season		$g\ cm^{-3}$	
0 to 5	1.27	1.20	1.25
5 to 10	1.27	1.20	1.25
10 to 20	1.57	1.25	1.35
20 to 30	1.43	1.47	1.44
SEM		0.05	
Source of Variation			
Treatment	0.11		
Depth	<0.01		
Treatment x Depth	0.11		
2013 grazing season			
0 to 5	1.46	1.57	1.39
5 to 10	1.46	1.57	1.39
10 to 20	1.65	1.58	1.62
20 to 30	1.65	1.59	1.57
SEM		0.04	
Source of variation			
Treatment	0.14		
Depth	<0.01		
Treatment x Depth	0.36		

[1] GE: grazing exclusion; SysA: 1 cow ha^{-1} stocking rate and 100,000 kg LW ha^{-1} stocking density; SysB: 2.5 cows ha^{-1} stocking rate and 28,000 kg LW ha^{-1} stocking density.

Table 4.2. Soil organic carbon and total soil nitrogen stocks in pasture soils grazed under two management strategies and non-grazed.

Systems[1]	Stocks		
	SOC[2]	TSN[3]	C:N
	Mg ha^{-1}		
GE	42.0[a]	3.44[a]	21.0
SysA	47.4[a]	3.95[a]	18.7
SysB	63.0[b]	4.85[b]	19.4
SEM	3.8	0.2	
Source of Variation			
Treatment	<0.01	<0.01	0.06

[1]GE: grazing exclusion; SysA: 1 cow ha^{-1} stocking rate and 100,000 kg LW ha^{-1} stocking density; SysB: 2.5 cows ha^{-1} stocking rate and 28,000 kg LW ha^{-1} stocking density.
[2]SOC: soil organic carbon.
[3]TSN: total soil nitrogen
Means differences within columns indicated by letters ($P < 0.05$).

Table 4.3. GHG exchange from pasture soils and animal and total C equivalent flux from pasture sites managed under two different management strategies and non-grazed pasture sites.

Systems[1]	Soil emissions F_{CO2}[2]		F_{N2O}[3]		$F_{CH4soil}$[4]		Animal Emissions $F_{CH4cows}$[5]		Total emissions Ceq_{flux}[6]	
	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
2011 grazing system					kg C ha^{-1} d^{-1}					
GE	-	-	-	-	-	-	-	-		
SysA	10.54	6.07[a]*	1.16	0.80	-0.18	-0.07	-	-	11.35	6.77[a]*
SysB	9.74	7.64[b]*	1.19	1.59	-0.21	0.06*	-	-	10.69	9.57[b]
SEM	0.41		0.32		0.04				0.64	
Source of Variation										
Treatment	0.28		0.07		0.25				0.03	
Period	<0.01		0.96		0.02				<0.01	
Treatment × Period	<0.01		0.08		0.04				<0.01	
2012 grazing season										
GE	8.24	9.13	0.11	0.05	0.01[a]	0.003	0	0	8.38[a]	9.18[a]
SysA	8.04	8.31	0.44	0.08	0.14[b]	0.08	3.28	2.26	12.06[b]	10.75[ab]
SysB	7.11	9.26*	0.31	0.19	0.08[a]	0.07	4.89	3.43	12.17[b]	12.73[b]
SEM	0.50		0.11		0.04		0.63		0.57	
Source of Variation										
Treatment	0.43		0.19		<0.01		0.12		<0.01	
Period	0.15		0.09		0.38		0.03		0.97	
Treatment × Period	0.07		0.33		0.51		0.68		0.06	

Table 4.3. (cont’d)

Systems[1]	Soil emissions F_{CO2}[2]		F_{N2O}[3]		$F_{CH4soil}$[4]		Animal Emissions $F_{CH4cows}$[5]		Total emissions Ceq_{flux}[6]	
	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
2013 grazing season	kg C ha^{-1} d^{-1}									
GE	19.96	8.57^{a}*	0.96^{a}	-0.88	0.20	-0.17			20.77^{a}	7.71^{a}*
SysA	19.72	10.75^{ab}*	4.75^{b}	0.35*	0.23	0.33^{b}	1.93^{a}	1.61^{a}	26.13^{ab}	13.40^{b}*
SysB	21.49	14.97^{b}*	3.23^{b}	0.82	0.26	0.35^{b}	3.26^{b}	6.22^{b}	28.13^{b}	22.49^{c}
SEM	1.36		0.70		0.18		0.84		1.96	
Source of Variation										
Treatment	<0.01		<0.01		<0.01		0.02		<0.01	
Period	<0.01		<0.01		0.78		0.11		<0.01	
Treatment × Period	0.04		0.03		0.02		0.05		<0.01	

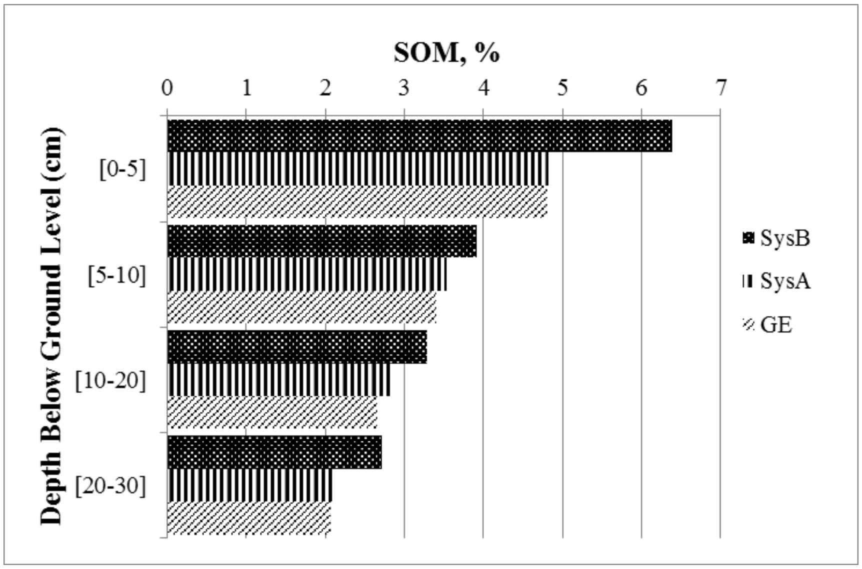
[1]GE: grazing exclusion; SysA: 1 cow ha^{-1} stocking rate and 100,000 kg LW ha^{-1} stocking density; SysB: 2.5 cows ha^{-1} stocking rate and 28,000 kg LW ha^{-1} stocking density.
[2]F_{CO2}: C equivalent flux of CO_2 from the soil.
[3]F_{N2O}: C equivalent flux of N_2O from the soil.
[4]$F_{CH4soil}$: C equivalent flux of CH_4 from the soil.
[5]$F_{CH4cows}$: C equivalent flux of enteric CH_4 from the cows.
[6]Ceq_{flux}: net GHG exchange in terms of C equivalent.
Means differences within columns indicated by letters ($P < 0.05$). Means differences within rows indicated by symbols ($P < 0.05$).

Table 4.4. Daily GHG emissions from soil and animal managed under two different grazing strategies and non-grazed pasture sites.

Systems[1]	Soil emissions			Animal Emissions	Total emissions
	F_{CO2}[2]	F_{N2O}[3]	$F_{CH4soil}$[4]	$F_{CH4cows}$[5]	Ceq_{flux}[6]
			kg C ha^{-1} d^{-1}		
GE	9.87[a]	0.25[a]	-0.09[a]	0	8.88[a]
SysA	10.03[a]	1.56[b]	0.13[b]	2.09[a]	13.96[b]
SysB	11.47[b]	1.17[b]	0.10[b]	4.91[b]	15.34[b]
SEM	0.66	0.32	0.08	1.09	0.74
Source of Variation					
Treatment	0.17	<0.01	<0.01	0.02	<0.01

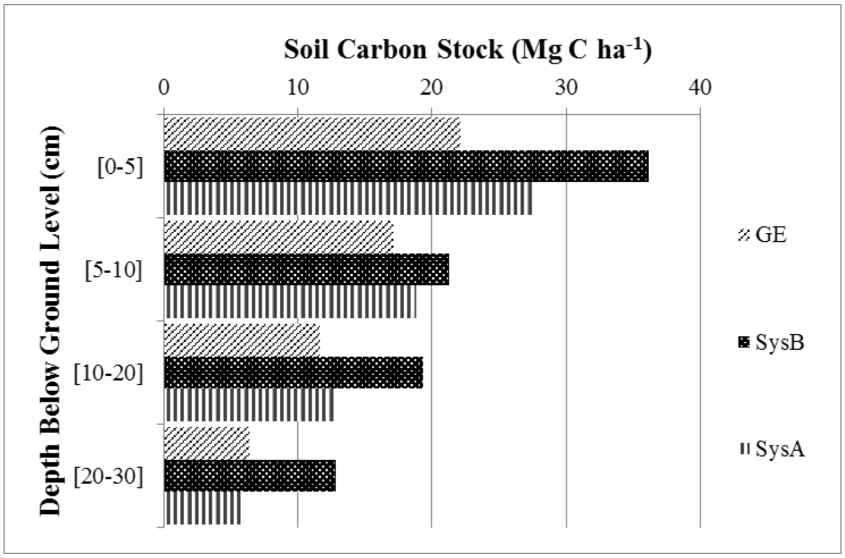
[1]GE: grazing exclusion; SysA: 1 cow ha^{-1} stocking rate and 100,000 kg LW ha^{-1} stocking density; SysB: 2.5 cows ha^{-1} stocking rate and 28,000 kg LW ha^{-1} stocking density.
[2]F_{CO2}: C equivalent flux of CO_2 from the soil.
[3]F_{N2O}: C equivalent flux of N_2O from the soil.
[4]$F_{CH4soil}$: C equivalent flux of CH_4 from the soil.
[5]$F_{CH4cows}$: C equivalent flux of enteric CH_4 from the cows.
[6]Ceq_{flux}: net GHG exchange in terms of C equivalent.
Means differences within columns indicated by letters ($P < 0.05$).

Figure 4.1. Soil organic matter in pasture soils grazed with two different grazing management strategies and non-grazed pastures sites.



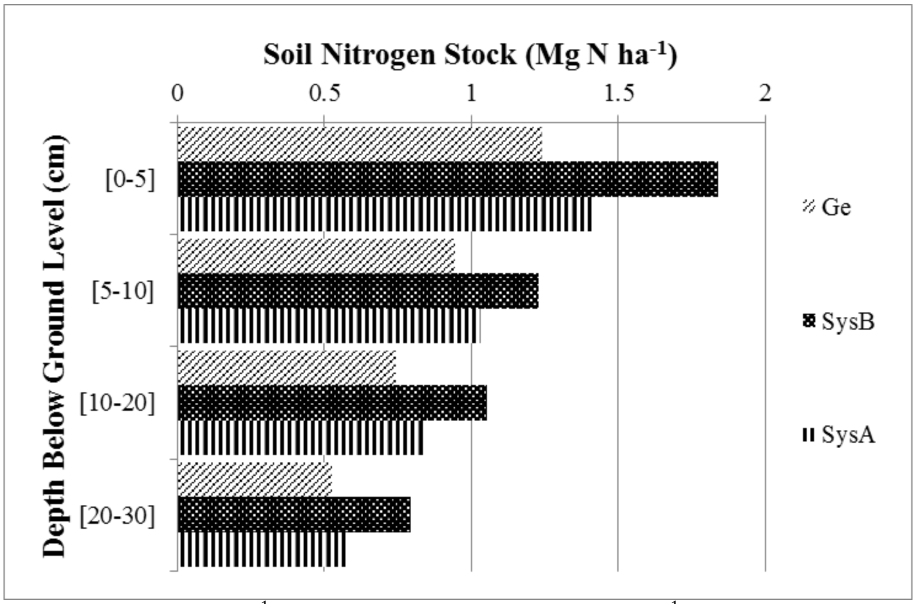
GE: grazing exclusion; SysA: 1 cow ha^{-1} stocking rate and 100,000 kg LW ha^{-1} stocking density; SysB: 2.5 cows ha^{-1} stocking rate and 28,000 kg LW ha^{-1} stocking density.

Figure 4.2. Soil carbon stock in pasture soils grazed with two different grazing management strategies and non-grazed pastures sites.



GE: grazing exclusion; SysA: 1 cow ha^{-1} stocking rate and 100,000 kg LW ha^{-1} stocking density; SysB: 2.5 cows ha^{-1} stocking rate and 28,000 kg LW ha^{-1} stocking density.

Figure 4.3. Total soil nitrogen stock along the soil profile in pasture soils grazed with two different grazing management strategies and non-grazed pastures sites.



GE: grazing exclusion; SysA: 1 cow ha^{-1} stocking rate and 100,000 kg LW ha^{-1} stocking density; SysB: 2.5 cows ha^{-1} stocking rate and 28,000 kg LW ha^{-1} stocking density.

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