Assessment of greenhouse gas emissions in dairy cows fed with five forage systems

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ABSTRACT
Thirty Holstein cows were arranged in a randomised block design for 287 days and fed rations of five forage systems: Italian ryegrass in rotation with corn (S1), hybrid ryegrass mixtures with three legumes in rotation with corn (S2) or sorghum (S3), red clover with hybrid (S4), and Perennial (S5) ryegrass pastures. In systems S1, S2, and S3, the cows remained in the barn throughout the study period and were fed total mixed ration (TMR). In systems 4 and 5, the cows grazed in a pasture and were only fed at the barn when grazing was not possible. All rations were balanced with a low quantity of concentrate at a forage/concentrate ration of approximately 80/20. Feed intake, milk quantity, and milk quality test data were entered in the program CAP2® to calculate the test-related carbon footprint. Results, based on 287 days trial, expressed as grams of CO2 equivalent per kilogram of fat and protein corrected milk (FPCM), were 724 (S1), 701 (S2), 764 (S3), 507 (S4), and 528 (S5). Actually, the lower results in S4 and S5 than results for S1, S2 and S3 seem more related to the inclusion of the carbon sequestration and land-use change issues than more inputs/more but not enough milk production. When soybean meal is imported, the findings highlight that soybean meal emission factor due to land use change (LUC) strongly affected CO2 equivalent emissions in systems S1, S2 and S3 where 670, 625 and 628 kilograms of soybean meal were consumed by cows in the trial.

HIGHLIGHTS
• The higher productivity of double-cropping systems does not compensate for the higher amount of greenhouse gases that they emit, measured as CO2-equivalent emissions per kilogram of FPCM.
• Pasture-based systems emit lower quantities of greenhouse gases per kilogram of FPCM, but their milk yield is lower than that of more intensive systems.
• Emission factors differ considerably due to differences in soil use. The result of greenhouse gas emissions from the system will largely depend on how these emission factors are analysed.

Introduction

Importance of GHG emissions

Greenhouse gas (GHG) emissions have attracted considerable research interest in recent years. Decarbonisation and GHG emissions reduction are the cornerstones of policies that are being designed at all levels. In the agricultural sector, the GHG-reduction policy is also highly important and is included in various European frameworks, such as the “Green Deal” (Comisión Europea [European Commission] 2021), which aims at reaching emissions neutrality in the European agroforestry complex by 2050. This arduous work entails great efforts from many players in the sector and a scientific, and technical consensus on methods and parameters for measuring these GHGs is crucial. As agro-livestock systems are complex, their analysis requires instruments and extensive knowledge on how interactions between soil, plants, animals, and the atmosphere maintain balance (Grossi et al. 2019) and on how, as in any system, variations in some
components affect the others, thus complicating the process of finding simple solutions.

**Aim of the study**

The aim of the study was to compare five forage dairy systems in terms of carbon footprint by monitoring the animals’ feed intake, milk yield and GHG forages emissions as evaluation parameters. The tests conducted in this study were analysed accordingly to the life cycle assessment. Some studies, Little et al. (2017), compared different fed systems for dairy cows and a holistic perspective is highlighted for a better understanding of dairy farm systems.

**Assessment of GHG through Life-Cycle assessment (LCA)**

Life cycle assessment provides a rigorous framework to assess a product or system against a range of environmental impact categories from the ‘cradle to the grave’. Life cycle assessment has been increasingly applied to agricultural products, including those from livestock. Pirlo (2012) reviewed milk carbon footprint with a wide scope organic vs conventional, intensive vs extensive and the effect of milk productivity are tackled at this review.

**Material and methods**

**Location**

The experiment was conducted at the Agricultural Research Centre of Mabegondo (Centro de Investigaciones Agrarias de Mabegondo – CIAM; A Coruña, Galicia, Spain). The animals were tested in 2019, and some crops were grown and harvested in the previous year.

**Forage systems**

The study design has employed forage systems common in milk production in Galicia. Understandably, the wide variability of milk production systems existing in the territory cannot be completely reproduced under experimental conditions, hence the number of experimental units and groups have been limited to testing only five forage systems that are the most common in Galicia (Flores-Calvete et al. 2017). The following systems were studied:

**Italian ryegrass in rotation with corn (S1)**

In the same plot, two crops were grown. The summer crop was forage corn sown in May and harvested in September for silage, this crop is sown in rotation with pasture. In the S1 system, Italian ryegrass, Westworld variety, was sown in early Autumn and ensiled in a single silage cut in April, leaving time to prepare the land to sow corn again in May. These two forages were used together with a commercial concentrate to prepare the cow rations. The animals tested in this system remained in the barn throughout lactation.

**Hybrid ryegrass mixture with three legumes in rotation with corn (S2)**

This system could be regarded as an improved version of S1 because the only difference is the substitution of the winter crop Italian ryegrass by a hybrid ryegrass mixture with three trifoliate legumes, namely balansa clover, crimson clover, and Persian clover. Sowing and harvesting times are the same as in system S1. As in S1, the cows used in this test remained confined throughout the study period that overlapped with their complete lactation cycle. In the cow ration, these two forages were used together with a commercial concentrate.

**Hybrid ryegrass mixture with three legumes in rotation with sorghum (S3)**

In this drought-resistant system, corn is replaced by sorghum. Owing to its physiological characteristics, this summer crop has increased resistance to periods of low rainfall. For cultivation and harvesting dates for silage, the dynamics of this system are similar to those of the previous two groups; the animals of this group also remained in the barn throughout lactation. In the cow ration, these two forages were used together with a commercial concentrate.

**Red clover with hybrid ryegrass pasture (S4)**

Given its characteristics, this crop is sown every other year in the autumn. After planting, the crop was used for grazing during the study period. Whenever grazing was not possible, the animals remained in the barn and consumed forage ration previously prepared in the same grazing plot. The cows grazed for 2/3 of the study period, remaining in the barn for 1/3 due to the lack of pasture in the plots. The forage ration was supplemented with concentrate and its characteristics
depending on whether the cows consumed silage or pasture.

Perennial ryegrass pasture (S5)
This grazing crop is sown in the autumn and usually lasts more than five years, depending on the specific circumstances. As in system S4, the animals remained grazing on the plot when the amount of grass in the pasture sufficed for their feeding; otherwise, the animals were confined and consumed silage as forage ration prepared with the forage that was produced in the field where they grazed. The forage ration was supplemented with a concentrate composed of raw materials, complementing the characteristics of the forage offered to the animals under the same conditions as in the previous group.

Forage production
An area of 3.5 hectares was assigned to each system. The five assigned plots had similar soil quality and fertilisation levels. We describe below the work performed for each crop used in the different systems.

Italian ryegrass (IR)
Tillage was performed at the beginning of October 2017. No need for liming was detected by soil analysis. Deep fertilisation was performed by applying 108 kg K₂O, and 12 m³ slurry per hectare. A dose of 40 kg/ha of Italian ryegrass (Lolium multiflorum Lam.) cv. Promenade was sown. An herbicide specific for broad-leaved plants was used where necessary for weed control. At the beginning of March, 61 kg/ha of nitrogen was applied using a broadcast spreader. The crop was harvested in a single cut in mid-April.

Hybrid ryegrass mixture with three legumes (R3L)
The tasks described below were performed for this crop in the plots corresponding to systems S2 and S3, without any difference in their execution. After tillage in mid-October 2017, 118 kg K₂O, 17 kg N, and 9 m³ slurry were applied per hectare as basal dressing fertiliser. The composition and dose of the mixture was hybrid ryegrass (Lolium hybridum H.), cv. Barsilo (13 kg/ha), crimson clover (Trifolium incarnatum L.), cv. Inta (6 kg/ha), Persian clover (Trifolium resupinatum L., ssp. resupinatum), cv. Kyambro (3 kg/ha), and balansa clover (Trifolium michelianum S.), cv. Bolta (3 kg/ha). Weed control was performed using a specific herbicide for such purposes. The crop was harvested in a single cut at the beginning of May for silage.

Forage corn
For the corn (Zea mais L.) used in systems S1 and S2, the sowing and harvesting tasks were the same in both plots, albeit differing in the dressing guidelines that will be specified in each case. Tillage was performed between the first and second weeks of May in the year before the experiment with the animals. The basal dressing consisted of 93 kg N, 70 P₂O₅, 32 K₂O, and 25 m³ slurry per hectare for S1, with 68 kg N, 56 P₂O₅, 7 K₂O, and 32 m³ slurry for S2. After sowing, the necessary pesticides were applied against the most common pests. Between late June and early July, broadcasting fertilisation was performed with 20 kg N/ha only in the corn of system 1. The corn was ensiled as a whole plant in trench silos at the end of September, following the usual practices for this purpose.

Sorghum
Forage Sorghum (Sorghum bicolour L.) cv. Moench was sown in the Spring of 2017 as a summer crop. This crop was grown on the surface that was vacated by the mixture of hybrid ryegrass and annual clovers after they were harvested in the plot of system S3. At the beginning of May, tillage was performed, followed by basal dressing, with doses of 48 kg N, 28 kg P₂O₅, 162 kg K₂O, and 28 m³ slurry per hectare. The forage sorghum variety PR849F (Pioneer®) was sown in mid-May, at a dose of 250,000 seeds per hectare. After sowing, pesticides were applied as needed for cultivation. The crop was harvested in late September and ensiled in trench silos following the usual practices recommended for ensiling forage species.

Red clover (RC)
The forages used for feeding the cows of group S4 were red clover with hybrid ryegrass and silage from the same pasture. In mid-September 2017, tillage was performed, applying the usual practices for this sowing, followed by basal dressing with 100 kg P₂O₅ and 150 kg K₂O per hectare. No liming was needed after analysing the soil. In late September, after tillage and fertilisation, red clover (Trifolium pratense L.) cv. Lemmon (25 kg/ha) and hybrid ryegrass (Lolium hybridum H.), cv. Barsilo (18 kg/ha) were sown. Both
pre- and post-emergent herbicides were used for weed control.

In 2018, the crop was harvested in three cuts for silage, the first in late May, the second in early June, and the third in late August. The forage was ensiled into round bales under good conditions. These round bales were used as the ration for the animals of system 4 when grazing was not feasible.

In 2019, during the study period, rotational grazing was performed on the plot, ensiling any surplus. In this plot, the only fertiliser was the droppings of the animals when grazing, together with 14 m$^3$ slurry generated by the cows in the barn.

**Perennial ryegrass (Rin)**

The forages used to feed the animals of group S5 were perennial ryegrass pasture and silage. In mid-September 2017, before sowing, the usual tillage tasks were performed. The soil was limed at a dose of 2000 kg/ha based on prior analysis. The basal dressing was performed by applying 75 kg P$_2$O$_5$ and 150 kg K$_2$O per hectare, sowing perennial ryegrass (Lolium perenne L.) cv. Barsintra at a dose of 35 kg/ha.

The plot was managed similarly to the plots sown with red clover, with rotational grazing and reserving part of the plots for ensiling. The ensiling procedure was the same as that described for the red clover. In contrast to system S4, 101 kg N, 13 P$_2$O$_5$, and 12 m$^3$ slurry per ha were applied during the study period in this system.

**Animals**

In total, 30 Holstein multiparous cows of the CIAM experimental herd, with a moderate milking potential (9,000 – 10,000 kg/lactation), were used in this study. The winter-calving cows started the experiment in March, averaging 19 days in milk (DIM) (36.8% CV), with an average daily production of 33.8 L (18.3% CV), live weight of 618.9 kg (12.0% CV), and a body condition of 2.88 (0/5 scale) (7.0% CV). The randomised complete block design consisted of 5 treatments, one per system and 6 replicates (cows). The cows were grouped into 5 batches of 6 animals, ensuring that the groups were as homogeneous as possible in terms of the aforementioned variables.

**Cow management**

The animals of groups S1, S2, and S3 remained in the barn through the experiment. The kilos of feed consumed daily per animal were controlled using an automated feeding system. Groups S4 and S5, during the grazing cycles, only entered the livestock facilities after morning milking to eat the concentrate and then returned to the pasture. The concentrate was offered in the experimental barn with individual feeders so that all cows ate only their previously measured feed ration. When the cows in these groups could not graze, they remained in the barn, with the forage intake being controlled as that in groups S1, S2, and S3. During the study period, cows in group S4 were grazing 183 days and 104 days remained in the barn, meanwhile for the S5 group cows were 197 days and 90 days, respectively.

In all groups, throughout the experiment, daily milking was performed at 8:00 am and 7:00 pm. The experimental period spanned from lactation day 22, average per group, to lactation day 309. The first 21 days of lactation were reserved as the pre-experimental period to enable the animals to adapt to the rations and management. 287 days was the length of the trial for every group.

**Cow feeding**

Each of the five groups received a different diet, all based on the forages described in the previous section. The ration offered to each group varied with the lactation status of the cows throughout the experiment, albeit without varying the ingredients. The following rations (ratios on Dry Matter based) were offered:

**Group S1:** Total mixed ration (TMR) consisted of 40% corn silage, 42% Italian ryegrass silage, 1% hay, 5% concentrate, and 12% soybean meal 44. This ration corresponds to the middle third of lactation, from 115 to 209 days in milk. In the first third of lactation, from 22 to 114 days in milk, the amount of concentrate and soybean meal was 40% higher than in the middle period, and the amount of forage was lower in the proportion corresponding to the increase in concentrate and soybean meal. In the last third of lactation, from 210 to 309 days in milk, the amount of concentrate and soybean meal was decreased by 40%, thus increasing the proportion of forage. This proportionality in the formulation was repeated in groups S2 and S3.

**Group S2:** TMR consisted of 40% corn silage, 41% silage of hybrid ryegrass mixture with three annual clovers, 1% hay, 9% concentrate, and 9% soybean meal 44 in the middle period of lactation.

**Group S3:** TMR consisted of 39% sorghum silage, 42% silage of hybrid ryegrass mixture with three annual clovers, 2% hay, 8% concentrate, and 9% soybean meal 44 in the middle period of lactation.
meal 44, also referring to the middle period of lactation.

Group S4: TMR consisted of 82% silage of red clover and hybrid ryegrass, and 18% concentrate in the period when the cows remained in the barn. When the cows grazed in the pasture, the ration consisted of red clover and hybrid ryegrass “ad libitum”, 1 kg hay, and 5 kilograms of a mixture consisting of beet pulp meal (70%) and barley meal (30%) per cow and day.

Group S5: TMR consisted of 83% silage of perennial ryegrass and 17% concentrate in the period when the cows remained in the barn. When the cows grazed in the pasture, the ration consisted of perennial ryegrass “ad libitum”, 1 kg hay, and 5 kilograms of a mixture of beet pulp meal (70%), and barley meal (30%) per cow per day.

The pasture consumed by groups S4 and S5 was managed following the rotational grazing system, always offering the animals a quantity somewhat higher than their potential intake. The cows in both groups remained in the pasture during the day and night. Every day, before the cows returned from the morning milking, the pasture state, height, density, and quality were observed, and the area offered for that day was delimited with an electrified wire.

**Sample collection and data analysis**

**Feed**

Samples of the unifeed ration that the animals consumed in the barn were collected weekly, and samples of each ingredient that composed the rations were collected monthly.

The nutrient composition of these samples was determined using NIR technology. The spectral information of the samples, dried and ground, was assessed using a Foss NIRSystem 6500 monochromator spectrophotometer (Foss NIRSystem, Silver Spring, Washington, USA). When groups S4 and S5 were grazing, samples of the pasture on offer (pre-grazing) and the rejected pasture (post-grazing) were collected three days a week. The pre- and post-grazing samples were dried in the laboratory, ground, and analysed using NIR technology to determine their physicochemical composition.

**Milk**

Cow milk yield was recorded every day of the experiment using automatic gauges placed in the milking parlour. From each cow, samples of milk from the daily milking were collected weekly. The samples were analysed at the Galician Interprofessional Laboratory of Milk Analysis (Laboratorio Interprofesional Galego de Análise do Leite – LIGAL) to determine the physicochemical composition by Fourier-Transform Mid-Infrared (FT-MIR) Spectroscopy (Milkoscan, FOSS, Hillerød, Denmark).

**Feed intake measurements**

Dry matter intake (DMI) was monitored when the cows were in the barn by combining daily data provided by the monitoring feeder system and the %DM of the rations assessed by sampling TMR rations weekly.

When the cows were grazing, the daily intake was estimated by applying the following formula (NRC National Research Council 2001):

\[
DMI \text{ (kgDM/day)} = (0.372 \times 4\%FCM) + (0.0968 \times LW^{0.75}) \\
	\times (1 - e^{-0.192 \times \left( LW + 3.67 \right)})
\]

where 4%FCM is 4% fat-corrected milk yield (kg); LV live is the weight of the cow (kg); LW is lactation week.

The amount of grass ingested by the animals was determined by subtracting the kilograms of dry matter consumed daily by the cows in the barn from the result of applying the previous formula.

**Animal weight and body condition**

The live weight and body condition of the cows were measured on two consecutive days after the morning milking and monthly. Body condition was measured using the method described by Edmonson et al. (1989) and expressed using a five-point scale where 1 is extremely thin and 5 is obese.

**Greenhouse gas (GHG) emissions calculation program**

The program used to measure the GHG was the CAP2ER® (Calcul Automatisé des Performances Environnementales en Elevage de Ruminants [Automated Calculation of Environmental Performance in Ruminant Breeding]), level 2, of the French Livestock Institute (Institute de l’Elevage – IDELE). CAP2ER® (IDELE. 2018) is a tool that helps decision-making in dairy farms by performing a high-precision evaluation. Based on this evaluation, factors of the environmental footprint of the farm are assessed and used to quantify margins of progress and design action plans. The program is based on the concept of Life Cycle Assessment (LCA) and consists of evaluating the environmental impact of the whole milk farm by considering the
inputs and outputs of material flows and products of the farm. The analysis is limited exclusively to the dairy farm, not including the uses or transport of the products produced outside the farm for their transformation and introduction in the market.

The data required by the program are categorised into three groups:

- **Herd:** Census data including animals in production, dry cows, bulls, and rearing; timing of animal handling as defined by the management; type of barn; ration offered to the animals in different times; milk yield and physicochemical quality.

- **Feed:** referring to the forage produced on the farm, type of crop, surface area, yields, and mineral and organic fertilizers; in addition, forage and concentrate purchases outside the farm are included.

- **Energy expenditure:** Electric energy consumption; fuel consumed in agricultural work including contract work; the use of renewable energy.

Three aspects are considered key in the program, namely enteric emissions, emissions from manure, and emissions from the crops and inputs used on the farm.

- **Enteric emissions**

  These are determined using the following formula (Sauvant and Nozière 2013):

  \[
  \text{Enteric } CH_4 \ (g \ CH_4/kg \ OMD) = 45.42 - 6.66 \times DMI \% LW + 0.75 \times (DMI \% LW)^2 + 19.65 \times COP - 35 \times (COP)^2 - 2.69 \times DMI \% LW \times COP
  \]

  where DMI is the daily dry matter intake, COP is the proportion of concentrate in the ration, and LW is the live weight. All these data have been provided or calculated by the model; subsequently, and depending on yield, breed, and other parameters, the Organic Matter Digestibility (OMD) of the complete ration was calculated, thus determining the amount of enteric CH4 emitted by the animals.

- **Emissions from manure**

  The following formula was used to calculate emissions from manure (IPCC 2019):

  \[
  CH_4 \ \text{manure}(Kg/LU/year) = \sum NDOM \times 0.67 \times B_{0,j} \times MCF_j \times FG_j
  \]

  where LU is livestock unit; NDOM is the non-digestible organic matter of the ratio; Bo is the maximum methane production capacity of the managed system (j); MCF is the methane conversion factor that depends on the temperature and system; FG is the percentage of manure treated in system j. The program calculated the NDOM as a function of milk yield and feed intake.

- **Emission factors for inputs and crops**

  For the forages and crops that are produced on the farm, emission factors are calculated as a function of the emissions assigned to the different inputs necessary for producing these forages, organic and inorganic fertilisers, type of work, and amount of dry matter produced. A carbon sequestration factor will be subtracted from this emitted amount for each crop, this sequestration factor depends on the culture and its length (Dollé et al. 2013) Only the emission factor of the feed consumed by the animals will be considered. The model disregards the emission factors of the forages that are produced on a farm but not consumed by the cows in the measured period. For each outsourced raw material (forage or concentrate), associated emission factors were retrieved from AGRIBALYSE or ECOALIM databases, both based on the Life Cycle Inventory.

**Statistical analysis**

The random block was the experimental design used for this trial with six experimental units (cows) per treatment. One-way ANOVA analyses were used to determine significant difference between group S1 to S5 in terms of milk yield, protein and fat.

\[ Y_{ij} = \mu + T_i + \epsilon_{ij} \]

was the model to compare means where \( Y_{ij} \) represents the j-th observation \((j = 1,2,\ldots,n_i)\) on the i-th treatment \((i = 1,2,\ldots,k \text{ levels})\); \( \mu \) represents parameters common to all treatments (parity, days in milk, milk yield in previous lactation, body condition score and body weight); \( T_i \) represents the i-th treatment effect (S1 to S5) and \( \epsilon_{ij} \) represents the random error present in the j-th observation on the i-th treatment. The data were analysed using the statistical package SAS v.9.4 (SAS Institute, 2016)

**Results**

**Forages**

Annual and analytical yields of the different crops and forages used in the experiment. Corn had the highest yield of all crops (Table 1), surpassing sorghum by just over 15% in dry matter production. The winter
rotation crops in systems 1, 2, and 3 were Italian ryegrass (IR) and the hybrid ryegrass mixture with three legumes (R3L), harvested in a single cut for silage. IR had a 15% higher yield per hectare than the crops of the three annual legumes (R3L). The rotation was performed in the total experimental surface (3.5 ha per system). System 1 produced a surplus of 2.6 t of corn and 0.4 t of IR, S2 a surplus of 2.5 t of corn and 2.0 t of sorghum and S3 a surplus of 0.1 t of R3L, all values are expressed as dry matter.

Finn et al. (2013) conducted a three-year European study in thirty-one different locations, confirming that the combined biomass produced by the mixed species, legumes, and grasses, is higher than that produced by the individual crops. The yield of legume species mixed with grasses was also similar with 50 kg/ha of inorganic N to grasses monoculture with 450 kg/ha of inorganic N as Nyfeler et al. (2009) reported at this study.

The yield in t of DM (Table 2) of Perennial ryegrass (Rin) in system 5 (10.7 t/ha) surpassed the yield of system 4 (8.6 t/ha) with red clover and hybrid ryegrass in

2.1 t per ha. The use of the land associated with each system was adjusted to grazing needs, ensiling the forage that the animals were unable to consume while grazing. Part of this ensiled forage was consumed in the test, in its entirety in S4, and with a surplus of 0.9 t of dry matter in S5 whose emissions were disregarded when calculating the carbon footprint.

Corn digestibility (Table 3) in the test was 15 points higher than sorghum digestibility (Behling Neto et al. 2017). In the winter crops of the rotations, the R3L mixture contained a protein percentage 3.34 points higher than IR. Red clover and hybrid ryegrass silage and perennial ryegrass silage analytical results are similar except in organic matter digestibility, where perennial ryegrass silage is 4.3 points higher. In grazing systems 4 and 5 (Table 4), the forage analysis results were similar in analytical terms.

### Rations

In systems 1, 2, and 3, the animals consumed unified rations during the 287 days of the monitoring period in the barn that varied as a function of the average days in milk of the group of cows. Table 5 outlines the dry matter intake per cow and group.

The animals of systems 4 and 5 that combined housing and grazing consumed silage and commercial concentrate when they were in the barn. During the

### Table 1. Forage production of systems 1, 2, and 3 (t DM/ha).

| 2017/2018 | Group | Crop | Previous crop | t DM/ha |
|-----------|-------|------|---------------|---------|
| Summer crop | S1 | Corn | Italian ryegrass | 12.58 |
| | S2 | Corn | R3L | 12.32 |
| | S3 | Sorghum | R3L | 10.65 |
| Winter crop | S1 | Italian ryegrass | Corn | 6.57 |
| | S2 | R3L | Corn | 5.63 |
| | S3 | R3L | Sorghum | 5.74 |

**Table 2. Forage production of systems 4 and 5 (t DM/ha).**

| 2018/2019 | Group | Pasture | Silage | Total |
|-----------|-------|---------|--------|-------|
| Perennial pasture | S4 | t DM/ha | 5.0 | 3.6 | 8.6 |
| Red clover and hybrid ryegrass | S5 | t DM/ha | 5.3 | 5.4 | 10.7 |
| Perennial ryegrass | Yield per use | 1.2 | 4.2 | – |
| No. uses | 4.4 | 1.3 | 5.7 |

**Table 3. Chemical characterisation of forage silages.**

| Crop sample | OM | CP | ADF | NDF | OMD | STAR |
|-------------|----|----|-----|-----|------|------|
| Corn silage (n = 11) | 96.7 | 5.2 | 4.4% | 40.8 | 70.2 | 33.8 |
| Sorghum silage (n = 12) | 96.8 | 6.9 | 31.0 | 54.1 | 55.0 | 14.0 |
| Italian ryegrass silage (n = 13) | 90.8 | 8.8 | 33.4 | 45.9 | 70.0 | Mean |
| R3L silage (n = 14) | 89.8 | 12.1 | 36.0 | 47.0 | 68.2 | Mean |
| Red clover and hybrid ryegrass silage (n = 15) | 92.5 | 8.6 | 37.4 | 56.8 | 65.3 | Mean |
| Perennial ryegrass silage (n = 16) | 90.3 | 8.4 | 34.1 | 52.4 | 69.6 | Mean |
| Hay (n = 17) | 92.7 | 7.2 | 46.9 | 71.7 | 38.9 | Mean |

n: number of samples; OM: organic matter (%DM); CP: crude protein (%DM); ADF: acid detergent fibre (%DM); NDF: neutral detergent fibre (%DM); OMD: organic matter digestibility (%); STAR: starch (%DM); CV: coefficient of variation; R3L: a mixture of hybrid ryegrass with three annual clovers.
Table 5. Dry matter intake per cow and system (*).  

| Ingredient       | S1   | S2   | S3   | S4   | S5   |
|------------------|------|------|------|------|------|
| Corn silage      | 2,404| 2,388| –    | –    | –    |
| Sorghum silage   | –    | –    | 2,405| –    | –    |
| Italian ryegrass silage | 2,448| –    | –    | –    | –    |
| R3L silage       | –    | 2,440| 2,563| –    | –    |
| Hybrid ryegrass and red clover pasture | –    | –    | –    | 2,929| –    |
| Perennial ryegrass pasture | –    | –    | –    | 3,110| –    |
| Red clover and hybrid ryegrass silage | –    | –    | 1,836| –    | –    |
| Hay              | 9    | 9    | 109  | 167  | 175  |
| Concentrate      | 23.5%| CP   | 352  | 427  | 415  | 324  | 234  |
| Soybean meal     | 670  | 625  | 628  | –    | –    |
| Barley meal      | –    | –    | –    | 596  | 624  |
| TOTAL            | 5,883| 5,889| 6,120| 6,107| 5,708|

(* Data entered in CAP2er program; Data expressed as kg. DM/cow (287 days); R3L: hybrid ryegrass mixture with three annual clovers.

Table 6. Analytical results of the TMR of the different systems.  

| Group (n = 41) | OM   | CP   | ADF  | NDF  | OMD  | STAR | CF   |
|---------------|------|------|------|------|------|------|------|
| S1            | 92.9 | 12.9 | 26.6 | 42.7 | 69.5 | 17.5 | 2.8  |
| S2            | 92.3 | 13.7 | 27.4 | 41.8 | 68.1 | 18.0 | 2.7  |
| S3            | 92.5 | 14.9 | 31.5 | 47.0 | 62.6 | 11.5 | 2.4  |
| S4            | 89.7 | 13.6 | 31.4 | 46.7 | 64.4 | 7.4  | 3.0  |
| S5            | 88.9 | 13.9 | 27.7 | 43.0 | 69.7 | 7.8  | 3.1  |

n: number of samples; OM: organic matter (%DM); CP: crude protein (%DM); ADF: acid detergent fibre (%DM); NDF: neutral detergent fibre (%DM); OMD: organic matter digestibility (%); STAR: starch (%DM); CF: crude fat (%DM); CV: coefficient of variation; R3L: hybrid ryegrass mixture with three annual clovers.

The data for the 287 days of the experiment were entered in the program CAP2er® (Tables 8 and 9).

Gross GHG emission factors depending on animal husbandry, fertilisers and energy are higher in those systems with higher inputs. S1, S2 and S3 do not produce milk enough to offset these higher input emissions, furthermore, enteric fermentation GHG, linked to feeding intake, is the highest in system 3, a combination of these two factors make system 3 with 764 g of CO₂ equivalent per litre of FPCM the system with higher gross GHG emissions. The ability of systems 4 and 5 to sink carbon as a result of permanent grassland used in these grazed-based systems make these to systems the lowest in terms of carbon footprint per unit of milk produced.

Discussion

The comparison of the milk yield between systems 1, 2, and 3 shows that the cows of system 3 had the highest dry matter intake but the lowest yield because this ration was less digestible than those of systems 1 and 2 (69.5%; 68.1% and 62.6% of OMD in rations S1, S2 and S3). In turn, the OMD of this ration was lower because the digestibility of sorghum silage (55.0%) is lower than that of corn silage (70.2%).

The results of GHG emitted by different systems are comparable between groups but not to data measured in other dairy farms because, in the present study, GHG emissions were measured only for lactating cows, disregarding both replacement heifers and dry cows among other factors with a strong impact on GHG.

Forage system

S3 is the system that emits the most GHG per kilogram of FPCM combined with the lowest milk yield, producing 5% less milk than the system with the highest yield, even though the dry matter intake was 5% higher in system 3 than in systems 1 and 2. Accordingly, the energy capacity of sorghum silage and therefore the milk yield are much lower.

System S2, as expected, given the introduction of the R3L mixture in rotation with corn, produced milk...
at the same yield level as S1. However, introducing legumes in rotation increases the protein content of the forage ration and therefore enables us to decrease the protein supply in concentrate by using less soybean. In addition, the amount of synthetic-fertiliser nitrogen used in system 2 (85 kg N/ha) was lower than that used in system 1 (174 kg N/ha) (Báez et al. 2018). Since the amount of slurry in both systems was similar, 37 and 41 m³/ha in systems 1 and 2, respectively, the difference in the synthetic fertiliser together with the lower amount of exogenous protein accounts for the lower GHG emissions in the second system than in the first.

In the two grazing systems, the S5 based on pasture and perennial ryegrass silage produced more milk with fewer kilograms of intake per cow but was not enough to compensate for the higher fertiliser nitrogen used in this system than in S4 (101 kg vs. 0 kg). The use of legumes resulted in GHG reduction as noted by comparing the two systems. In the study by Nyfeler et al. (2009), the effect of the symbiosis between clovers and grasses was shown, with the

### Table 8. Data entered in CAP2ER®.

|                | S1       | S2       | S3       | S4       | S5       |
|----------------|----------|----------|----------|----------|----------|
| General data   |          |          |          |          |          |
| No. animals    | 6        | 6        | 6        | 6        | 6        |
| Surface (ha)   | 3.5      | 3.5      | 3.5      | 3.5      | 3.5      |
| Duration (days)| 287      | 287      | 287      | 287      | 287      |
| No. barn days  | 287      | 287      | 287      | 104      | 183      |
| No. grazing days | 0      | 0        | 0        | 90       | 197      |
| Live weight    | 640      | 621      | 645      | 628      | 630      |
| Milk           |          |          |          |          |          |
| Milk yield per cow (L)* | 7,564  | 8,180    | 7,347    | 7,482    | 7,299    |
| Fat (g/L)      | 44.6     | 39.4     | 43.4     | 39.4     | 41.0     |
| Crude protein (g/L) | 32.4    | 32.4     | 32.8     | 30.7     | 33.7     |
| Crops (t/DM year) (%) legume |          |          |          |          |          |
| Silage corn in rotation | 12.58  | 12.3     | –        | –        | –        |
| Silage sorghum in rotation | 10.65  | –        | –        | –        | –        |
| IR in rotation with corn | 6.57    | –        | –        | –        | –        |
| R3L in rotation with corn/sorghum | 5.63 (80%) | 5.74 (80%) | –          | –        | –        |
| Perennial pastures | –        | –        | 8.66 (57%) | 10.72    |          |
| Mineral fertilisation (kg/ha N-P₂O₅-K₂O) |          |          |          |          |          |
| Silage corn in rotation | 113-70-32 | 68-56-7  | –        | –        | –        |
| Silage sorghum in rotation | –        | –        | 48-28-162 | –        | –        |
| IR in rotation with corn | 61-0-108 | –        | –        | –        | –        |
| R3L in rotation with corn/sorghum | –        | 17-0-118 | 17-0-118 | –        | –        |
| Perennial pastures | –        | –        | 0-0-0    | 101-13-0 |          |
| Organic fertilisation (m³/ha) |          |          |          |          |          |
| Silage corn in rotation | 25      | 32       | –        | –        | –        |
| Silage sorghum in rotation | –        | –        | 28       | –        | –        |
| IR in rotation with corn | 12      | –        | –        | –        | –        |
| R3L in rotation with corn/sorghum | –        | 9        | 9        | –        | –        |
| Perennial pastures | –        | –        | 14**     | 12**     |          |
| Surplus forage (t/DM) |          |          |          |          |          |
| Corn silage    | 2.6      | 2.5      | –        | –        | –        |
| Sorghum silage | –        | –        | 2.0      | –        | –        |
| IR silage      | 0.4      | –        | –        | –        | –        |
| R3L silage     | –        | –        | 0.1      | –        | –        |
| RC silage      | –        | –        | –        | –        | –        |
| Rin silage     | –        | –        | –        | 0.9      |          |

*Milk yield (287 days); **Slurry generated by cows inside barns. The others are manure in prairies; IR: Italian ryegrass. R3L: hybrid ryegrass mixture with three annual clovers; RC: red clover mixture with hybrid ryegrass; Rin: perennial ryegrass.

### Table 9. GHG emissions of the study systems were calculated with CAP2ER®.

| GHG emissions and stock (g CO₂ eq/l FPCM) | S1      | S2      | S3      | S4      | S5      |
|------------------------------------------|---------|---------|---------|---------|---------|
| GHG emissions Animals, fertilisers and energy | 324     | 271     | 294     | 237     | 228     |
| Enteric fermentation                      | 400     | 430     | 470     | 430     | 420     |
| Total gross GHG emissions                | 724     | 701     | 764     | 667     | 648     |
| Carbon stock                             | 0       | 0       | 0       | (160)   | (120)   |
| Net GHG emissions                        | 724     | 701     | 764     | 507     | 528     |

GHG: Green House Gases.
FPCM: Milk yield (287 days) 4.0% fat, 3.3% crude protein-corrected milk.
nitrogen-fixing capacity being maximised in mixtures containing 40–60% of legumes, the composition similar to that used in system 4 that was the only system in which synthetic fertiliser was not used.

Jensen et al. (2012) concluded that N₂O emissions from grass mixtures with legumes were lower than those from pure legumes and that pastures with grasses emit the most N₂O. Considering the milk production system as a whole, a better nitrogen adjustment both in cow rations and in crop fertilisation will increase efficiency and reduce GHG emissions (Le Gall et al. 2009). Halving nitrogen use in a farm in Brittany had no negative impact on the farm yields (Raison et al. 2008).

Other variables to consider regarding the viability of the proposed systems are the area and the amount of excess forage in each system, having a good capacity to feed more animals. Systems 1 and 2 produced the most surplus forage, 3.0 and 2.5 t of dry matter respectively, system 3 produced an excess of 2.1 t, system 5 produced 0.9 t and system 4 generated no surplus forage. Thus, with a limited surface area, systems 1 and 2 produced the most milk, whereas system 4, based on grazing and legumes, had the lowest capacity to produce forage, feed cows, and therefore to yield milk. Kellermann and Salhofer (2014) compared dairy farms with different yields and systems, based either on permanent pastures or on crop rotation, and concluded that farms without associated crops, corn or sorghum in our case, had competitive advantages in issues such as biodiversity, carbon sequestration, or landscape, but land scarcity and lower milk yield per unit area threaten this system.

For this reason, land availability is a key factor in farm resilience that ensures the continuity of farms as they become more resistant to the ups and downs of the market (EIP-Agri 2018a). The protein self-sufficiency of farms or the amount of food produced on the farm itself is an important indicator for assessing the degree of farm resilience to events such as increases in prices of raw materials or future penalties applied by the industry for CO₂-equivalent emissions.

Systems with lower emissions usually are lower productive, therefore to offset this output disadvantage some tax systems (Moberg 2019) should be arranged. Milk production based on grazing produces externalities to be considered and paid (EIP-Agri 2018b).

The yield per crop unit, the feeding capacity, and the necessary inputs of the crops are the key factors in understanding the responses of different systems to GHG emissions.

### Emission factors

The emission factors for the different materials (Table 10), compound feed and purchased forages should be valid for the test in question because they were retrieved from French reference tables (AGRIBALYSE and ECOALIM) and therefore relevant to the geoclimatic context as similar as possible to that of Galicia.

Emission factors are also influenced by rotations (Ma et al. 2012). As shown in corn rotations with legumes, CO₂-equivalent emissions per kilogram of corn produced in rotation with legumes/corn with 100 FU nitrogen were 40% lower than those of corn as a single crop with 200 kilograms of nitrogen, with a similar corn grain yield. In our experiment, the program also showed that legume rotation with corn improved results, system 1 has lower GHG emissions than system 2 (724 vs 701). This difference is partly due to the decreased use of chemical fertilisers, in turn resulting from the nitrogen-fixing capacity of rhizobia in symbiosis with legumes. Thus, N₂O emissions are lower given the lower Calcium Ammonium Nitrate (CAN) volatilisation. This good performance of legumes in terms of GHG is not enough to offset the lower digestibility of sorghum compared to maize, therefore S3 emissions are higher than those in S1 and S2 even using legumes as a winter crop.

We discuss soybean separately given the great differences in the final emissions results associated with this crop. The massive use of soybean in animal feed has now spread this crop over large areas, implying a Land Use Change (LUC). The LUC factor strongly

### Table 10. The most relevant emissions factors of CAP'2ER©.

| Product (emissions factor units)                          | Emissions factor |
|-----------------------------------------------------------|------------------|
| Concentrates                                              |                  |
| Soybean meal 44 (kg CO₂ eq/kg)                            | 1.383            |
| Barley meal (kg CO₂ eq/kg)                                | 0.389            |
| Dehydrated beet pulp (kg CO₂ eq/kg)                       | 0.150            |
| Dairy-cow concentrate with 22% CP (kg CO₂ eq/kg)          | 0.694            |
| Energy                                                    |                  |
| Electricity (kg CO₂ eq/kWh)                               | 0.055            |
| Diesel (kg CO₂ eq/L)                                      | 3.250            |
| Inorganic fertilisers                                     |                  |
| Calcium ammonium nitrate (kg CO₂ eq/kg N)                 | 6.209            |
| Phosphoric fertiliser (kg CO₂ eq/kg P₂O₅)                 | 0.568            |
| Potassic fertiliser (kg CO₂ eq/kg K₂O)                    | 0.444            |

CP: crude protein.
affects the calculation of the soybean emission factor. Castanheira and Freire (2013) studied the emission factors of soybean produced in Latin America and exported to Europe, observing very different values depending on the crop origin and on the cropping system when considering a soybean emission factor ranging from 0.1 to 17.8 kg CO2-equivalent emissions per kilogram of soybean. Farmland is the critical factor. As such, soybean grown in humid tropical regions where the tropical forest is transformed into farmland has the highest emission factor. If the LUC factor was disregarded when making these calculations, the soybean emission factor ranged from 0.3 to 0.6 kilograms of CO2-equivalent emissions. These values are similar to those for local or regional crops and raw materials.

Therefore, selecting the soybean emission factor is a major decision. Table 11 outlines the emission factors; the first factor, 1.38, is provided by the program CAP’2ER® by default, whereas the second factor, 3.74, is the value assigned to soybean imported in Spain by GFLI® (Global Metrics For Sustainable Feed 2021), clearly showing the considerable difference in CO2-equivalent emissions per kilogram of FPCM when applying different factors. When applying the highest soy-emission factor, the carbon footprint of the systems that use soybean in animal feed increases by more than 25%.

**Conclusions**

Crop rotation systems with confined cows’ GHG emissions are higher in CO2 equivalents per kilogram of FPCM than those of grazing-based systems. The higher milk production does not offset the increase in emissions from the more intensive systems. Grazing-based systems CO2 equivalents emissions are lower than those from intensive systems, but the former have lower milk yields than the latter. Therefore, without incentives, these systems are highly penalised.

The use of legumes species is highly appealing for reducing GHG emissions due to the greater protein self-sufficiency and lower use of chemical fertilisers on the farms.

Whether or not LUCs are considered in soybean emission factors has a decisive effect on the calculated emissions results of each of the proposed systems, decisively penalising the systems that use this raw material.

Increasing self-sufficient in protein production and replacing raw materials with high emission factors by using local or regional industrial by-products will reduce the risk of high CO2-equivalent emissions linked to the land-use change (LUC).

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**Data availability statement**

The data that support the findings of this study are available from the corresponding author (V.G.S.) upon reasonable request.

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**Table 11. GHG emissions of the study systems were calculated with CAP’2ER® with two emissions factors for soybean meal 44%.

| EF soybean meal 44 = 1.38 (kg CO2 eq/kg) | S1  | S2  | S3  | S4  | S5  |
|------------------------------------------|-----|-----|-----|-----|-----|
| EF soybean meal 44 = 3.74 (kg CO2 eq/kg) |    |     |     |     |     |
| Emissions increase                       | 215 | 198 | 209 | 0   | 0   |
| Emissions increase (%)                   | 30% | 28% | 27% | 0%  | 0%  |
| Net GHG emissions (g CO2 eq./l FPCM)    |    |     |     |     |     |
| S1                                       | 724 | 701 | 764 | 507 | 528 |
| S2                                       | 939 | 899 | 973 | 507 | 528 |
| S3                                       |     |     |     |     |     |
| S4                                       |     |     |     |     |     |
| S5                                       |     |     |     |     |     |

EF: emissions factor; FPCM: 4.0% fat, 3.3% protein corrected milk.


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