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Optimizing Soil, Water and Nutrient Use Efficiency in Integrated Cropping–Livestock Production Systems

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Nuclear Techniques in Food and Agriculture

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OPTIMIZING SOIL, WATER AND NUTRIENT USE EFFICIENCY IN INTEGRATED CROPPING–LIVESTOCK PRODUCTION SYSTEMS

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PREPARED BY THE
JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

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FOREWORD

Continuous nutrient mining, monocropping and poor farming practices are still the norm in many developing countries, and they generally lead to declining soil fertility and quality, a loss of crop productivity, and falling incomes. Equipping farmers, especially in developing countries, with knowledge of techniques for maintaining or improving soil fertility through best farming practices can support sustainable crop production. Improving soil fertility by retaining more carbon and essential plant nutrients is key to making soil more resilient to a changing climate. The integrated cropping–livestock system is a simple and highly beneficial practice for good soil management that enriches soil with essential plant nutrients and improves soil organic matter and soil biological activities, leading to increased soil fertility and improvements in soil structure and stability. The adoption of an integrated cropping–livestock system (e.g. growing nitrogen fixing legumes in rotation, recycling organic residues and manure, and using animal grazing to minimize dependence on chemical fertilizers), combined with strategic use of chemical fertilizers and water, and the avoidance of unnecessary cultivation to preserve carbon and nutrients in soil, can conserve nutrients and thereby provide better growing environments for crop growth and enhanced crop productivity.

This publication presents the results of a coordinated research project entitled Optimizing Soil, Water and Nutrient Use Efficiency in Integrated Cropping–Livestock Production Systems. The overall objective of the project was to enhance food security and rural livelihoods by improving resource use efficiency and sustainability of integrated cropping–livestock systems under a changing climate. Other objectives included optimizing water and nutrient use efficiency in integrated cropping–livestock production systems; identifying the potential for improving soil quality and fertility in such systems; assessing their socioeconomic and environmental benefits, and their influence on greenhouse gas emissions, soil carbon sequestration and water quality; and strengthening the capacity of Member States to use isotopic and nuclear techniques and to develop soil, water and nutrient management options for farmers to improve management of integrated cropping–livestock systems. The results of the project provide insights into building soil resilience by conserving more nutrients and carbon, and into reducing greenhouse gas emissions from agriculture.

The IAEA officer responsible for this publication was M. Zaman of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

CONTENTS

SUMMARY

BACKGROUND

The rationale for the Coordinated Research Project (CRP) "Optimizing Soil, Water and Nutrient Use Efficiency in Integrated Cropping-Livestock Production Systems (D1.20.12)" was to investigate mutually beneficial synergies in the production of crops and livestock for human consumption. In modern intensive agricultural systems, crop and livestock husbandries are often conducted as separate enterprises. However, traditional small scale agriculture was based on the raising of crops and livestock on the same family farm. Many advantages can accrue from side by side crop-livestock farm activities. For example, protein rich grain legume residues or cereal straw can be fed to livestock, while livestock manure can be used as fertiliser for crops. In this CRP, the opportunities for obtaining benefits from integrated cropping-livestock production systems were investigated, with the aid of strategically applied nuclear techniques to obtain unique information on soil-plant-animal interactions. Studies from six countries in three continents including Argentina, Brazil, India, Kenya, Uganda, and Uruguay are reported in this publication (Table 1).

OBJECTIVES

The main objective of the project was to enhance food security, improve soil fertility, and mitigate greenhouse gases (GHGs) from agriculture using integrated cropping-livestock systems under a changing climate. Additionally, the goals were to develop a package of technology for farmers to increase crop production and improve their livelihoods using nuclear and related techniques.

CRP ACHIEVEMENTS AND CONCLUSIONS

ARGENTINA

In Argentina, two farms with the same soil type and topographical position were compared. The integrated cropping-livestock farm produces lucerne and oats grazed by cattle alternating with a grain summer crops sequence of soybean and maize, while the continuous cropping (CC) farm produces soybean and maize in a continuous sequence. The same management has been carried out for more than 20 years on both farms, which were compared with a reference site (REF) under natural vegetation. Soil to a depth of 60 cm using an integrated cropping-livestock system (ICLS) showed an increase of 50% of soil organic carbon (SOC) stocks compared to CC. Differences in the $\delta^{13}C$ signatures of C_3 (lucerne, oats, soybean) and C_4 (maize) species indicate the relative contribution of C_3 and C_4 plants to the soil C pool (C_3 plants range in $\delta^{13}C$ values from –21 to –32‰, while for C_4 plants the range is –12 to –19‰). The $\delta^{13}C$ signatures in 0–5 cm for REF, ICLS and CC were –20.1, –20.0 and –19.8‰ respectively, while the values in the 5–20 cm soil depth for these treatments were –17.9, –17.6 and –17.3‰, respectively, and reflect a higher proportion of C_3 species in ICLS due to the incorporation of lucerne and oats. Systems having a perennial forage component are likely to show an increase in C sequestration, a process that can improve soil quality and the sustainability of crop production.

TABLE 1. EXPERIMENTAL VARIABLES

Country	Location	System[a]	Treatments	Livestock	Nuclear techniques[b]
Argentina	Humid pampas 33°39'S; 62°10'W	CC	Corn, soybean	None	$\delta^{13}C_{soil}$
		ICLS	Forages (lucerne, oats)	Cattle	
			Crops (soybean, maize)	None	
Brazil (Paraná state)	Ponta Grossa 25°07'S; 50°02'W	CC	Black oat, annual ryegrass, soybean, maize		^{63}Ni ECD (N_2O)
		ICLS	Black oat, annual ryegrass	Cattle	
	Pinhais 25°24'S; 49°07'W	Pasture	Dung and urine application	None	
		CC	Black oat, maize		
		ICLS	Black oat (forage), maize	Cattle	
	Castro 24°47'53''S, 49°57'42''W	CC	Annual ryegrass, maize (silage)	None	None
		ICLS	Annual ryegrass, maize (silage)	Cow	
India (Tamil Nadu State)	Kancheepuram, Trichy, Erode, Madurai	CC	Rice	None	None
		ICLS	Paddy straw, Hybrid Napier, *Desmanthus virgatus*	Cow, goat	

TABLE 1. (CONTINUED) EXPERIMENTAL VARIABLES

Country	Location	System[a]	Treatments	Livestock	Nuclear techniques[b]
Uganda	21’11.999” N, 3245’19.080” E	CC	Maize fertilized	None	None
			Maize unfertilized		
		ICLS	Maize-grazing rotation	Cattle	
Uruguay	Paysandú, 32°22'41"S; 58° 02' 50"W	CC	Wheat-soybean rotation	None	^{15}N (NUE, BNF)
		ICLS	Pasture-wheat-soybean sequence	Cow	
Kenya	Katumani, 01° 35'S, 37° 14'E	CC	Maize, maize-cowpea and maize-lablab intercrops	None	SMNP
		ICLS	+ Farmyard manure ± N, P		

Note: [a] **CC, continuous cropping; ICLS, integrated cropping-livestock system**
[b] **ECD, ^{63}Ni electron capture detector; SMNP, soil moisture neutron probe; NUE, N fertiliser use efficiency; BNF, legume biological N_2 fixation**

BRAZIL

The potential of ICLS to curb soil nitrous oxide (N_2O) and methane (CH_4) emissions and to sequester SOC was investigated in four field experiments located in east Paraná, southern Brazil. ICLS was characterized by winter pasture (oats plus ryegrass) under open grazing followed by a summer cash crop (soybean or maize). At Ponta Grossa, soil N_2O emission was reduced by almost one-half in ICLS compared to CC (1.1 vs. 2.0 kg N ha^{-1} yr^{-1}), but CH_4 fluxes and SOC stocks were not affected (107–109 t ha^{-1} to 1 m depth). At Pinhais, the nitrification inhibitor dicyandiamide (DCD) reduced the N_2O emission by 60–80% in autumn-winter when dissolved into urine, and by 45% in autumn when sprayed over a urine patch. N_2O emissions were reduced by 40% in ICLS relative to a continuous perennial pasture of guinea grass (14 vs. 23 kg N ha^{-1} in 1.5 years), and showed a trend to increase soil CH_4 consumption by about 80%. At the Castro site where the Ferralsol originally had a higher SOC stock (*ca.* 200 t ha^{-1}), there was no increase in SOC under ICLS. Overall, ICLS showed a potential to reduce soil N_2O emissions relative to continuous cropping or perennial pasture, but SOC stocks were not affected when the initial SOC was high.

INDIA

Experiments were carried out with dairy cows and goats over 5 years at 4 sites within four regions of Tamil Nadu State; north eastern, Cauvery delta, western and southern. Paddy was cultivated every year. Perennial Hybrid Napier grass (*Pennisetum* sp.) and leguminous fodder (*Desmanthus virgatus*) were also cultivated for feeding animals. Paddy straw was fed to cows but not to goats. Soil nutrients were conserved through the recycling of dung and urine. The System of Rice Intensification (SRI) developed by Tamil Nadu Agricultural University involving the cultivation of rice and drip irrigation of green fodder led to water use efficiency, with the input of water for every kg production of crop and green fodder being reduced. Integrated nutrient management by replacing synthetic nitrogen (N) fertiliser with farmyard manure along with phosphorus (P) and potassium (K) in SRI cultivation, maintained yield as well as soil fertility. By feeding the fodder grown in the nutrient recycled fields, the birth and weaning weights of calves increased by 20.5 and 10.5%, respectively. The adult weight, milk yield, and reproduction performance of dairy cattle likewise improved. In ICLS the average body weight, the birth weight, and average weaning weight of goats significantly increased in the fifth year compared with the first year of the project in all agro-climatic zones.

KENYA

Grain and biomass yield of maize planted in sole and intercropped systems (with cowpea or lablab) in conventional tillage or tied varied significantly between short (SR) and long (LR) bimodal rainy seasons. Yields were higher in SR than LR. Although increases in soil moisture with time and depth of profile under tied ridges were evident, tillage practices did not affect yields significantly across the seasons. Grain and biomass yield significantly increased when farm yard manure (FYM) supplemented with inorganic fertiliser at rates of 2.5 tons FYM and 20 kg N + 20 kg P_2O_5 ha^{-1} was applied compared to FYM alone. Higher grain production was obtained in sole cropping with conventional tillage, although higher biomass yields and quality were obtained from intercropped systems.

UGANDA

The effect of maize cultivation-cattle grazing rotation on (i) maize yield and plant nutrient uptake (ii) on physical and chemical properties of ferritic soils in Uganda and iii) farmers constraints to access quality livestock fodder were investigated. A completely randomised block design experiment was conducted on-farm between 2015 and 2017 for five seasons. The five treatments were namely: Continuous maize (fertilized and unfertilized), maize rotation with grazing, bare ground, and continuous grazing. In addition, a household survey was conducted among livestock farmers to assess the constraints they face in accessing and improving livestock fodder. The maize grazing rotation significantly reduced the gap between fertilized and unfertilised maize yield ($P < 0.05$). In comparison with the manure applied to the soil, potassium and calcium concentration in maize biomass and soil significantly increased compared with inorganic fertiliser ($P < 0.05$). In light of the above results, when access to NPK fertiliser is limited, we recommend the use of the maize grazing rotation for a better maize yield on ferralitic soils of central Uganda. Livestock fodders are plentiful but farmers mainly depend on unimproved pastures.

URUGUAY

Shifting from ICLS to CC under no-tillage after a long term period of change (25 years) showed either stable or higher wheat yields under CC than the ICLS system. There was a wheat response to N fertiliser in both rotations. The yields were higher in CC, although the optimum N rate was always lower in ICLS. Although, this would indicate that there was a quantity of residual N derived from pastures, some growth factors other than N limited the attainable yields in ICLS. N use efficiency (NUE) and recovery efficiency (RE) were higher under ICLS, but internal efficiency (IE) was lower, proving that factors other than N were limiting grain yield. Under such a rotation, which had a higher fresh C entry during the pasture phase, a greater sequestration of nutrients in soil organic matter, such as N, sulphur (S), and P, may have occurred. The ^{15}N recovery in wheat was significantly lower in ICLS than CC, suggesting that

^{15}N was immobilised due to the presence of fresh C, to sustain biological activity. The N balance (NB) in the wheat phase was negative and similar between systems, whereas in the soybean phase it was positive, but higher in the CC system, because the N input by biological N fixation (BNF) was higher in CC (72%) than in ICLS (64%). In the overall sequence, NB was similar in both systems (53 in CC and 56 kg N ha^{-1} in ICLS). Although NB was similar between systems, RE by crop productivity (N removed by grain) shows the lowest values under ICLS. On the other hand, the higher wheat yields were observed in CC, and also the highest N removed by grain that would be compensated by a higher N input by BNF in soybean crops. However, the NUE of the wheat crop grown under this rotation was very low, implying a long term higher risk of N losses. Such paradoxical results have been reported in other studies, indicating that some ecosystems, despite a low fertility (CC rotation), can still show high productivity, and by offering a way to maintain and improve soil fertility such as the ICLS rotation, the productivity does not improve.

GASEOUS EMISSIONS OF N_2O AND CH_4 FROM SUBTROPICAL BRAZILIAN SOIL UNDER INTEGRATED CROPPING-LIVESTOCK AND CROP-LIVESTOCK-FORESTRY PRODUCTION SYSTEMS

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Abstract

Agriculture and land use changes are two of the most important sources of greenhouse gases (GHGs) and in Brazil particularly they account for about two-thirds of the national emissions. However, expectations are that improved farming systems, like the integrated cropping-livestock system (ICLS), can combine food production with reduced GHG emissions. In this sense, we assessed the potential of ICLS for curbing soil nitrous oxide (N_2O) and methane (CH_4) emissions and sequestering soil organic carbon (SOC). The study was based on four field experiments conducted in east Paraná, Southern Brazil. Soil N_2O and CH_4 fluxes were measured in three experiments (static chamber method) and soil carbon accumulation to 1 m depth was assessed in two experiments. ICLS was characterized by winter pasture (oats plus ryegrass) under open grazing followed by a summer cash crop (soybean or maize). In the 3 year measurements in experiment 1, soil N_2O emission was reduced by almost one-half in ICLS compared to continuous cropping (1.1 vs. 2.0 kg N ha-1 yr^{-1}), but did not affect CH_4 fluxes and SOC stocks (107–109 t ha^{-1} to 1 m depth). In experiment 2, the N_2O emission factors for dairy cattle urine (0.34%) and dung (0.11%) were much lower than the default 2% of the Intergovernmental Panel on Climate Change (IPCC); and that the nitrification inhibitor dicyandiamide (DCD) reduced the N_2O emission by 60–80% in autumn-winter when dissolved into urine, and by 45% in autumn when sprayed over a urine patch. In experiment 3, where the Ferralsol originally had a higher SOC stock (ca. 200 t ha^{-1}), SOC increments with ICLS were not observed, but at least there was no decrease, which is also relevant. In experiment 4, the soil N_2O emissions were reduced by 40% in ICLS relative to a continuous perennial pasture of guineagrass (14 vs. 23 kg N ha^{-1} in 1.5 years), and indicated a trend to increase soil CH_4 consumption by about 80%. Overall, ICLS showed a potential to reduce soil N_2O emissions relative to continuous cropping or perennial pasture, but did not change SOC stocks when the initial stocks were high, and the N_2O emission factors for urine and dung were lower compared to the IPCC's 2%, which suggests that this default value could be revised for subtropical Brazil.

1. INTRODUCTION

Currently, there is a worldwide concern on recoupling C and N biogeochemical cycles so that humankind can benefit from the role played by the organic forms of those elements instead of being harmed by the excessive and uncontrolled concentrations of their small molecular forms such as CO_2, CH_4, N_2O – three important GHGs– and nitrate: a soluble anion that leads to serious problems related to water pollution. The ICLS is an intensive farming system characterised by the temporal rotation of crop and pasture in the same area that might help in the C and N recoupling process [1].

Approximately one-fourth of total global GHG emissions arise from Agriculture and land use changes [2]. These sources account for two-thirds of total emissions in Brazil. Agriculture makes up 92% and 78% of Brazil's N_2O and CH_4 emissions respectively [3, 4]. Hence, it is worth seeking strategies to mitigate emissions related to agriculture and land use changes.

No tillage ICLS systems are becoming increasingly significant in Brazil due to their innovative nature and the improved productivity (cattle, dairy and grain), and increased income of farmers associated with these systems [5]. Successful experiences of ICLS have also been reported for temperate and other subtropical environments [6–8]. Considering the potential of ICLS to expand in Brazil and worldwide, it is extremely important to obtain information on how this system may affect soil N_2O emissions and CH_4 emission/consumption, as well as soil C and N sequestration, and thus affect global warming contribution or mitigation. Some studies on ICLS suggest that grazing may intensify soil N_2O emissions as a result of animal trampling and the formation of anaerobic microsites in soil [9, 10], although others found that it may positively affect the stocks of soil C and thus mitigate CO_2 emissions [11, 12]. N_2O emissions were observed to have declined in Cerrado soil in Brazil under continuous cropping of ICLS according to Sato et al. [13]. ICLS offers opportunities to increase soil consumption rates of CH_4. The extent of these rates is likely controlled by soil moisture and inorganic N content [10].

A recent innovation in ICLS in Brazil is the inclusion of trees, with the aim to additionally produce wood or firewood and provide more thermal comfort to livestock by shadow [14, 15]. This system is called integrated cropping-livestock-forestry (ICLF), and practically nothing is known regarding soil N_2O and CH_4 emissions in such system. Since soil N_2O emission is a process that depends on temperature [16], there is an hypothesis that ICLF contributes to reducing the soil N_2O emission because of lower soil temperatures enabled by trees' shadow.

Another topic related to integrated farming systems that include grazing concerns N_2O emissions from cattle excreta (urine patch or dung pat). A default emission factor (EF) of about 2% was by the IPCC under its guidelines for national GHG inventories. It is thus assumed that of the total dung and urine produced by animals, 2% of the N is emitted as N_2O. While these are the soundest estimates for global emission data, the IPCC EFs may not be applicable for all nations. This has been substantiated by studies which found that the EF of N_2O for dung could be one-fifth of the EF of urine. [18–21]. This suggests that more studies are necessary on this topic, aiming at supporting a country specific EF for Brazil, similar to the Australian or New Zealand approach.

The general objective of this study was to identify strategies, like ICLS, to mitigate N_2O and CH_4 emission from soil in farming production systems of subtropical Brazil, including changes in SOC stocks.

2. MATERIALS AND METHODS

The study was developed in four field experiments carried out in Paraná state, Brazil, according to descriptions given below.

2.1. Experiment 1. Soil N_2O And CH_4 Emission, and Soil Organic Carbon (Ponta Grossa Site)

Activities took place in a field experiment (7 years old at the beginning of measurements) located in Ponta Grossa, Paraná State, Brazil (25°07'S; 50°02'W; altitude of 973 m). The climate is Cfb (Köppen) and the annual precipitation 1500 mm. Soil was classified as a Haplic Ferralsol [22], with sandy clay loam texture in 0–20 cm. Three soil use systems were evaluated, all under no-tillage management:

- Continuous cropping (CC), which consists of a succession of winter cover crops such as annual ryegrass (*Lolium multiflorum*) black oat (*Avena strigosa*) plus annual ryegrass (*Lolium multiflorum*) as winter cover crops, and soybean (*Glycine max*) or maize (*Zea mays*) as summer cash crops.
- Integrated cropping-livestock system (ICLS), with black oat plus annual ryegrass being grazed in three to four grazing cycles per winter by steers from the "Purunã" breed (open grazing). Each grazing cycle started when annual ryegrass was 20 cm high and finished two or three days later, when annual ryegrass was 10 cm high.
- Integrated cropping-livestock-forest (ICLF), similar to the previous, but with cultivation of eucalyptus (*Eucalyptus* sp.) and grevillea (*Grevillea* sp.) trees in rows with 14 m distance between each other.
- Native grassland (NG) adjacent to the experiment. Typical of southern Brazil grasslands with *Paspalum* and *Andropogon* grasses being extensively grazed by similar steers, but at a lower stocking rate.

The experimental design was a complete randomized block, with 3 replicates.

Air samples were collected over three years, at intervals varying from 1 to 21 days, depending on the phase of the agricultural cycle. Static PVC chambers of 40 cm height and 36 cm diameter were used for air sampling [23]. Chambers were deployed on metal-bases (two bases and chambers per plot) previously installed in a delineated mini-plot of 1.0 × 3.0 m inside the main plots. Bases were inserted 5 cm into the soil 48 h before the first sampling and kept in place continuously, except for sowing and harvesting.

Each air sampling session started at 9.00 am, the time that represents the mean flux of the day [24]. Air samples were taken with 20 ml polypropylene syringes every 15 minutes after chamber deployment (0, 15, 30 and 45 min) and later transferred into 12 ml glass vials. The base chamber was sealed with a rubber belt. Headspace temperature during deployment was monitored. Samples were analysed within 24 to 36 h after sampling, in a GC Chromatograph equipped with flame ionization detector (FID) and electron capture detector (ECD). GHG fluxes were estimated using linear model fitted to describe the gas concentration increase in the headspace over the 45 min chamber deployment. The cumulative annual emissions of N_2O and CH_4 were calculated by integrating the hourly emission fluxes measured during the sampling events.

For each air sampling, soil samples of the 0–5 cm layer (2.5 cm cores) were randomly collected within each experimental plot for measurement of gravimetric water content (105 ºC) and determination of water filled pore space (WFPS). At the beginning of measurements the soil bulk density in the 0–5 cm layer was also measured, by inserting 56 mm diameter and 30 mm height cylinders into the soil. The WFPS was calculated from gravimetric water content, the bulk density and a particle density of 2.65 t m^{-3}.

For the evaluation of SOC stocks, soil samples were collected in two sampling locations per plot at 0–5, 5–10, 10–20, 20–30, 30–45, 45–60, 60–80 and 80–100 cm depths. A metal frame of 25 × 50 cm with a 5 cm height was anchored into the soil surface to delineate each sampling position. Soil of each individual layer up to 30 cm depth was carefully dug with a spatula and weighed. Care was taken to remove soil of the exact dimensions, so the volume of each sampled layer was known. Flat rigid metal plates of 5, 10, 20 and 30 cm depth and 25 cm wide were used, adjusted over the anchored metal frame, to keep the correct depth and lateral dimensions of the trench. The layers between 30 and 100 cm depth were sampled with an auger of 21 cm diameter, beyond the floor of the opened trenches. The depth of augering was also made with reference to the anchored metal frame, which defined the soil surface.

After correction of soil moisture, and knowing the volume of each sample, the soil bulk density was calculated for every layer, based on the principle of the excavation method [25].

Samples were air dried, crushed by a wooden roll and sieved through a 2 mm mesh. A subsample of approximately 20 g was ground in a mortar to pass a 0.25 mm mesh and about 20 mg were analysed by dry combustion (Vario EL III) to determine the C and N concentrations.

Carbon stocks were corrected by the equivalent soil mass, taking the soil mass of native grassland as the reference [26].

2.2. Experiment 2. N_2O emissions from cattle urine and dung patches (Pinhais Site)

This experiment was carried out to measure N_2O-N emission factors of cow urine and dung patches in a pasture comprised mainly by *Paspalum*, *Axonopus* and *Pennisetum* grasses, at Canguiri Experimental Farm, Pinhais-PR, Brazil (25º24'S; 49º07'W; 912 m altitude). The clayey Cambisol contained 439 g kg^{-1} of clay, pH of 4.9 and 25 g kg^{-1} of organic carbon in the 0–20 cm layer and was free draining. The humid mesothermic subtropical climate (Cfb, Köppen) has a mean precipitation of 1408 mm per year (around 75 mm in August and 165 in January) and a mean monthly temperature varying from 12.2ºC in June to 19.9 in February. Frosts are frequent in winter.

Treatments consisted of the deposition of urine and fresh dung of dairy cows, at volume equivalent to one urination (1.7 litre) and mass equivalent to one defecation (2.3 kg), in circular micro plots of 0.083 m^2. Micro plots were delineated by a metal collar anchored 5 cm into the soil and with a free border of 3 cm. Urine and dung were collected from Friesian milking cows (live weight ~500 kg) fed on diets based on grazing (adjacent pasture with the same botanical composition of the experiment). The two excreta types were combined with or without application of the nitrification inhibitor DCD. When used, DCD was dissolved (mixed) into the excreta before its application, representing the maximum potential benefit of DCD use, or was sprayed on the excreta patch after its application, which represents the previous commercial form used in New Zealand, at a rate equivalent to 8 kg ha^{-1} of DCD [27]. Such combinations resulted in seven treatments, distributed in a randomized block design with four replicates:

- Control, soil without applications;
- U, urine application;
- U-DCDd, urine application with DCD dissolved;
- U-DCDs, urine application followed by DCD sprayed;
- D, dung application;
- D-DCDd, dung application with DCD dissolved;
- D-DCDs, dung application followed by DCD sprayed.

These treatments were applied four times during one year, once per season: summer (08 Jan), autumn (16 Apr), winter (21 Jul), and spring (17 Oct). From autumn on, applications were in micro plots different from those of the preceding season, but in the same exclusion area. After excreta application, N_2O fluxes from soil, urine patches and dung pats were monitored over 63, 64, 60 and 68 days in summer, autumn, winter, and spring, respectively. Air sampling, handling and measurements were carried out according to the same method employed at the Ponta Grossa site, at 2–3 day intervals in the first 3 weeks after excreta application and 7–14 day intervals thereafter.

2.3. Experiment 3. Soil Organic Carbon (Castro Site)

Activities were carried out in a 9 year old field experiment located in Castro, Paraná State, southern Brazil (24º47'53''S, 49º57'42''W and elevation of 996 m). This experiment is situated approximately 40 km N from that of the Ponta Grossa site, in a similar humid subtropical climate (Cfb, Köppen). The soil type is a clayey Umbric Ferralsol.

Treatments included 3 soil use systems, set in main plots of 70 × 10 m, and 7 tillage systems, set in subplots of 10 × 10 m, arranged in a split plot randomized complete block design with 4 replicates. However, for this study we selected only 2 soil use systems combined with two-tillage system:

- Continuous cropping, with annual ryegrass (*Lolium multiflorum*) being used as a winter cover crop, which was desiccated at flowering. Maize was cropped for silage in summer.
- Integrated cropping-livestock system (ICLS), with annual-ryegrass being grazed in three to four grazing cycles per winter by Holstein or Jersey cows (open grazing). Each grazing cycle started when annual ryegrass was 20 cm high and finished two or three days later, when annual ryegrass was 10 cm high. The standing residue left after the last grazing cycle was desiccated with glyphosate herbicide. In summer, maize (*Zea mays* L.) was cropped for silage.

Each of this two soil use systems were combined with *conventional tillage* or *no-tillage*. For the conventional tillage plots, soil was tilled with 1 heavy disking operation (~15 cm deep) and two levelling disking operations (~10 cm deep) in spring to incorporate ryegrass biomass before planting maize. For the no-tillage plots, the ryegrass cover crop was desiccated with glyphosate herbicide, before planting maize.

Soil samples were collected for organic carbon assessment in the 0–5, 5–10, 10–20, 20–30, 30–45, 45–60, 60–80 and 80–100 cm layers, at two positions per plot. Samples of the upper three layers were collected with a spatula and those below 20 cm with an Edelman auger. Samples were air dried at ambient temperature, crushed with a wood roll and stored in plastic pots. About 20 g were further crushed in a mortar, to pass 0.5 mm mesh, and about 30 mg were analysed by dry combustion in a Vario EL elemental analyser to determine the SOC and total nitrogen concentrations.

Besides SOC and total nitrogen stocks up to 1 m depth, granulometric physical fractionation of soil organic matter was employed to the 0–5 cm soil layer to obtain sand plus particulate organic matter (sand-POM), silt and clay fractions. Also, the semiquinone concentration in the soil and in physical fractions of this 0–5 cm layer were measured with electron spin resonance (ESR technique), to obtain information on organic matter aromaticity.

2.4. Experiment 4. Soil N_2O and CH_4 Emission (Pinhais Site)

This was a 3 year old experiment (at the beginning of the study) located in Pinhais, Paraná State, Brazil (25°24'S; 49°07'W; altitude of 910 m). The climate is humid subtropical, Cfb, with an annual precipitation around 1500 mm. Soil was classified as a Haplic Cambisol, clayey texture in the 0–20 cm depth. The experiment belongs to the Federal University of Paraná.

Five soil use systems were evaluated, all of them under no-tillage soil management:

- Continuous cropping, which consisted of a succession of black oat (*Avena strigosa*) as a winter cover crop and maize (*Zea mays*) as a summer cash crop. This was regarded as the reference system.
- Pasture only, with guineagrass (*Urochloa maxima*, cv. Áries) being continuously grazed in summer and black oat (*Avena strigosa*) grazed in winter by beef cattle (open grazing).
- Integrated cropping-livestock system (ICLS), with black oat being grazed in the winter by beef cattle (open grazing) and maize cropped in summer as a cash crop.
- Integrated cropping-livestock-forest system (ICLF), similar to the previous system, but with cultivation of eucalyptus (*Eucalyptus* sp.) trees in rows.
- Integrated livestock-forest system (ILF), similar to pasture, but with cultivation of eucalyptus (*Eucalyptus* sp.) trees in rows.

The experimental design was a complete randomized block with 3 replicates. In treatments that included grazing, paddocks were 0.5–1.0 ha in area.

Air samples for the determination of N_2O and CH_4 were collected over ~1.5 years, at intervals varying from 1 to 21 days, depending on the phase of the crop or pasture cycle. Air sampling and chromatographic analysis were carried out according to the same methods employed at the Ponta Grossa site (Section 2.1).

3. RESULTS AND DISCUSSION

3.1. Experiment 1

3.1.1. Soil N_2O and CH_4 emission, and soil organic carbon (Ponta Grossa site)

During the soybean cycle in the first year, N_2O fluxes did not vary among treatments, with rates being < 30 μg N m^{-2} h^{-1}. During the leaf fall of soybean there was a slight tendency for the flux to increase (Fig. 1). In the following May, six days after N application to oat + ryegrass pasture (90 kg N ha^{-1}), a N_2O flux peak was observed in all treatments, and under continuous cropping it reached 70 μg N m^{-2} h^{-1}. About 15 days later, fluxes returned to background levels and so remained until the end of the pasture phase (end October). A second emission peak occurred after application of 200 kg N ha^{-1} to maize (January, second year) and again the highest flux was under continuous cropping (223 μg N m^{-2} h^{-1}). The next peak occurred soon after N application to winter oat + ryegrass pasture of the second year, following a similar trend observed in the previous year, also with continuous cropping emitting the highest flux (Fig. 1).

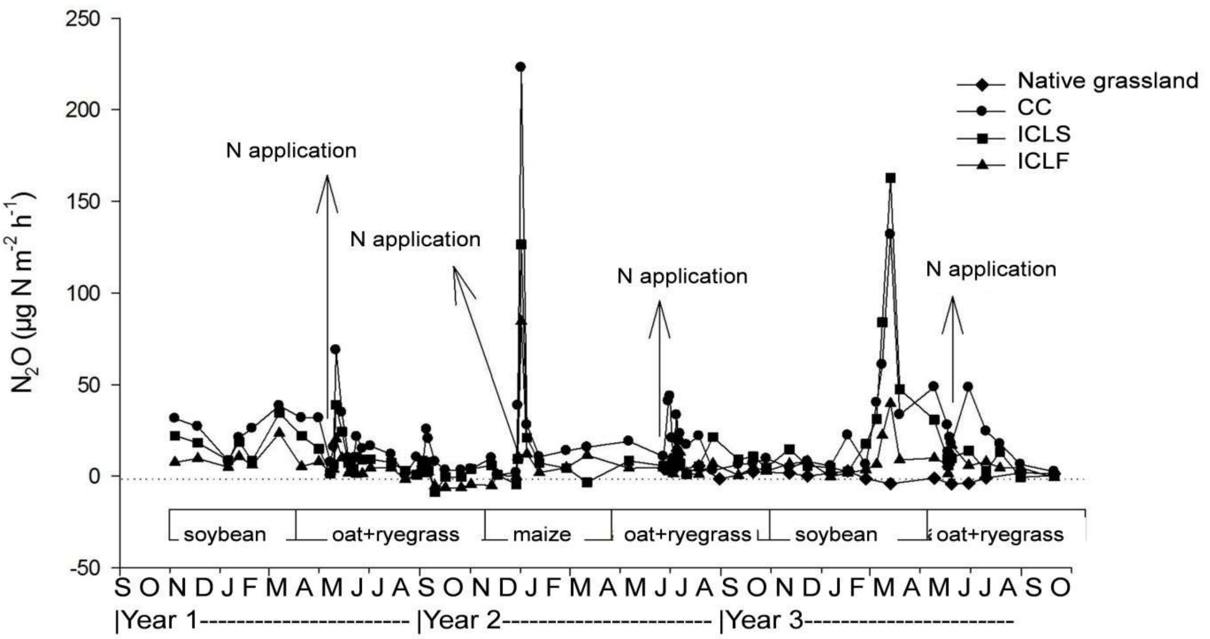

FIG. 1. Fluxes of N_2O over three years from a subtropical Ferralsol under native grassland, continuous cropping (CC), integrated cropping-livestock system (ICLS) and integrated cropping-livestock-forest (ICLF). Except native grassland, all land use systems were under no-tillage and the crop sequence depicted. Ponta Grossa-PR, Brazil.

During the third year, a strongly evident N_2O pulse occurred at the end of the soybean cycle (leaf fall) (Fig. 1), following a trend observed in the first year. It is not clear what caused such an N_2O emission peak with soybean, but hypotheses are the senescence of roots and nodules might have contributed to ammonium release by ammonification and a subsequent N_2O emission via nitrification and or denitrification [28].

The highest N_2O fluxes under continuous cropping compared to the integrated systems ICLS and ICLF were expressed in the cumulative N_2O emission averaged across the 3-year assessment period (Table 1), where 2.0 kg N-N_2O ha^{-1} yr^{-1} was emitted under continuous cropping, followed by ICLS (1.1 kg N-N_2O ha^{-1} yr^{-1}) and ICLF (0.6 kg N-N_2O ha^{-1} yr^{-1}). The higher N_2O fluxes under continuous cropping might be associated with the combined effects of higher nitrate, ammonium and water filled pore space (WFPS) in the soil (Fig. 2). The higher WFPS under continuous cropping might have created microsites favourable to anaerobiosis and denitrification. It is possible that the greater amount of crop residue on the surface of the CC soil at the end of the winter season (6.7 t ha^{-1}, measured in the first year, data not shown) favoured a higher soil water content and WFPS in summer cropping. In ICLF, the lowest N_2O emission compared to ICLS and continuous cropping is attributed possibly to the lowest soil temperature due to trees shade, which suggests a positive effect of this system at mitigating N_2O emissions. Finally, native grassland had the lowest N_2O emission (Table 1) and that is consistent with the lowest nitrate and ammonium concentrations and the lowest WFPS under this land use (Fig. 2), possibly because of better soil structural conditions allowing free aeration and, principally, because of no fertiliser N input.

TABLE 1. ANNUAL CUMULATIVE N_2O EMISSION FROM A SUBTROPICAL FERRALSOL UNDER NATIVE GRASSLAND, CONTINUOUS CROPPING, INTEGRATED CROPPING-LIVESTOCK AND INTEGRATED CROPPING-LIVESTOCK-FOREST. DATA FROM 3 YEAR MEASUREMENTS. PONTA GROSSA-PR, BRAZIL

Treatment	Year 1	Year 2	Year 3	Mean
		kg N_2O-N ha^{-1} $year^{-1}$		
Continuous cropping	1.8 a	1.6 a	2.3 a	2.0 a
Crop-livestock	1.2 b	0.7 b	1.5 b	1.1 b
Crop-livestock-forest	0.6 c	0.5 b	0.6 c	0.6 c
Native grassland			0.01	0.01

Note: Different lower-case letters within a column signify a significant difference ($p< 0.05$; Tukey)

It is interesting to note that all major emission peaks of N_2O occurred after N application to crops or pastures. Increasing N_2O emission following N fertilization, although concentrated in very few days, was significant and possibly the most important, and has been reported [29, 30] and attributed to nitrification and denitrification processes induced by the increase of inorganic N (NH_4^+ or NO_3^-) in soil [31]. Liebig et al. [32] reported that N fertilisation increased N_2O emissions by three-fold in pastures of the Great Plains, but enhanced deep storage of SOC. Our observation suggests that strategies to curb N_2O in those land use systems could begin by judiciously managing aspects related to timing, placement, source and mode of fertiliser application.

With respect to CH_4 fluxes, soil acted as a sink over most of the time (Fig. 3), which is consistent with the fact that the aerated condition of those soils favoured methanotrophic oxidation of CH_4 into CO_2 and blocked methanogenesis [33]. However, some noticeable emission peaks occurred, being generally associated to N-fertiliser application. Under elevated soil ammonium concentrations, which possibly occurred after N fertilisation, the methane monooxygenase enzyme of methane oxidizers turns to oxidise ammonium instead of CH_4, allowing this gas to evolve [34].

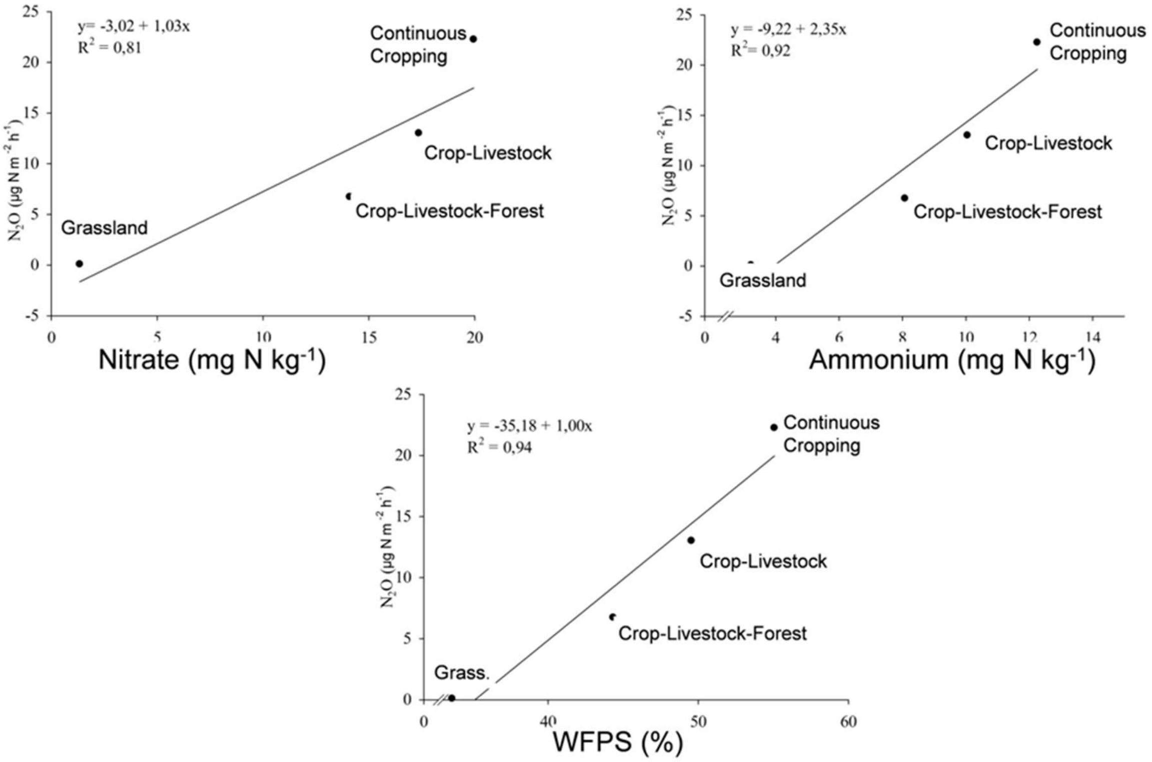

FIG. 2. Relation between the average annual N_2O flux and weighed mean of nitrate (a) and ammonium (b) concentrations and water filled pore space (c). Data from the 0–5 cm layer.

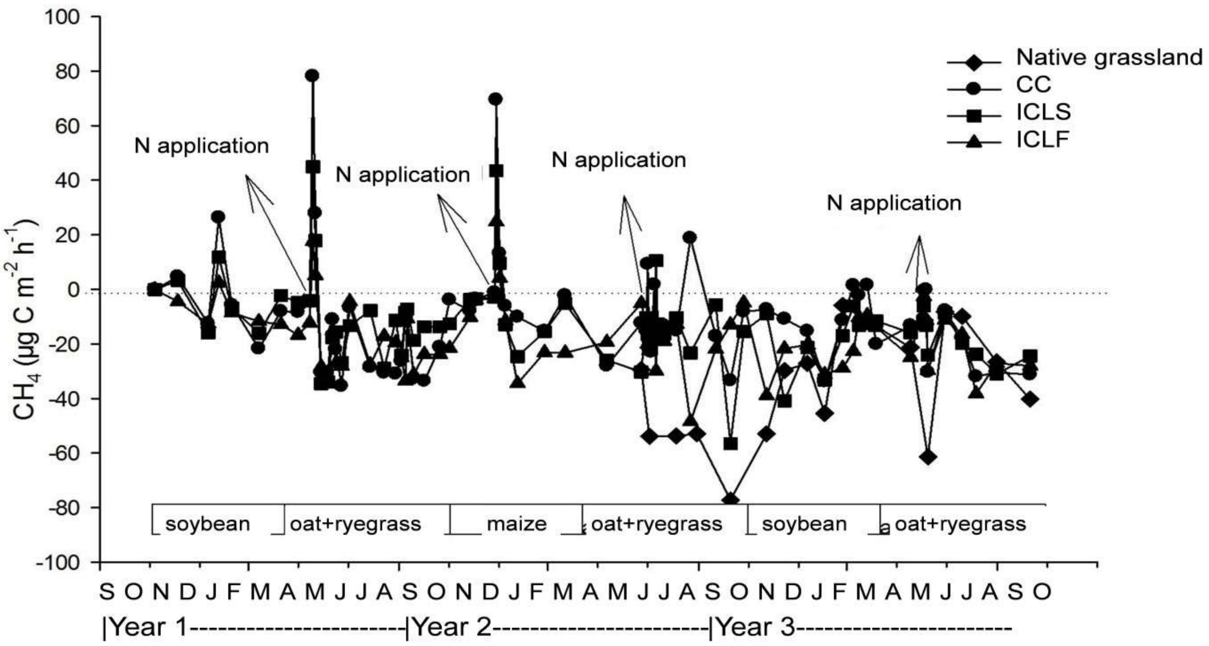

FIG. 3. Fluxes of CH_4 over three years from a subtropical Ferralsol under native grassland, continuous cropping (CC), integrated cropping-livestock system (ICLS) and integrated cropping-livestock-forest (ICLF). Except native grassland, all land use systems were under no-tillage and the crop sequence depicted. Ponta Grossa-PR, Brazil.

Over the monitored period, all soils acted as CH_4 sinks; but no significant difference in consumption of this gas could be evidenced among treatments. There was, however, a slight tendency of increasing consumption towards continuous cropping < ICLS < ICLP < NG (Table 2). The numerically higher consumption in NG might be attributed to the same reasons given for its lower N_2O emission, i.e. more aerated soil due to preserved structure and no fertiliser application.

TABLE 2. ANNUAL CUMULATIVE CH_4 EMISSION FROM A SUBTROPICAL FERRALSOL UNDER NATIVE GRASSLAND, CONTINUOUS CROPLAND, INTEGRATED CROPPING-LIVESTOCK AND INTEGRATED CROPPING-LIVESTOCK-FOREST. DATA FROM 3-YEAR MEASUREMENTS. PONTA GROSSA-PR, BRAZIL

Treatment	Year 1	Year 2	Year 3	Mean
		kg CH_4-C ha^{-1} $year^{-1}$		
Continuous cropping	–1.1 ^{ns}	–0.9 ^{ns}	–1.5 ^{ns}	–1.2 ^{ns}
Crop-livestock	–0.9	–1.4	–1.7	–1.4
Crop-livestock-forest	–1.4	–1.6	–1.9	–1.7
Native grassland			–2.8	–2.8

Note: Different lower-case letters within a column signify a significant difference ($p< 0.05$; Tukey)

The SOC stocks up to 1 m depth did not change significantly among continuous cropping, ICLS and ICLF and averaged 106 t ha^{-1}, which was significantly lower than the 125 t ha^{-1} in grassland (Fig. 4). Previous studies in the subtropical [35, 36, 37 and 38] or tropical regions [39] also reported no change in soil C stocks in ICLS areas. Yet, such results show at least that there is no negative effect of ICLS and its grazing on soil C [37], not compromising the other productive and economic advantages of ICLS [5, 40].

3.1.2. Conclusions

Results from these three years suggest that ICLS do have potential to reduce soil N_2O emission, even more when trees are included. However, no effects were observed on CH_4 emissions or SOC stocks, which show that there were no negative effects of ICLS and its grazing on soil C, and thus did not compromise the other productive and economic advantages of this system.

3.2. Experiment 2

3.2.1. N_2O emissions from cattle urine and dung patches (Pinhais site)

When urine was applied, N_2O fluxes increased sharply to peak at between 1.88–3.70 mg N m^{-2} h^{-1} 5–10 days after application, returning to background level 15–28 days after application (summer and spring), or 42–63 days after application (winter and autumn) (Fig. 5). In the control soil, fluxes varied between –0.04 and 0.13 mg N m^{-2} h^{-1} across the four seasons (Fig. 5). Cumulative emissions of N_2O were, on average, 23 times greater in urine patches versus the control soil (681 vs. 29 mg N m^{-2} $season^{-1}$, on average), resulting in a N_2O emission factor for urine that averaged 0.34% across the four seasons (Table 3). The N_2O emission factor was significantly lower in summer (0.19%), compared to the other seasons (0.35–0.45%) (Table 3).

With DCD dissolved in urine, N_2O fluxes also peaked within 5–10 days of application, although the magnitude was less than 50% of urine only, at between 0.79 to 1.58 mg N m^{-2} h^{-1} (Fig. 5). Moreover, post peak fluxes tended to return earlier to the background level when DCD was dissolved in urine (Fig. 5). Consequently, the N_2O emission factor for urine treated with DCD was significantly reduced by 60–82% in autumn (from 0.45 to 0.08%) and winter (from 0.35 to 0.14%) ($P<0.05$), but was not significantly affected in spring and summer (Table 3). Overall, the average N_2O emission factor across the four seasons was reduced by 62% with DCD dissolved, from 0.34 to 0.13% (Table 3).

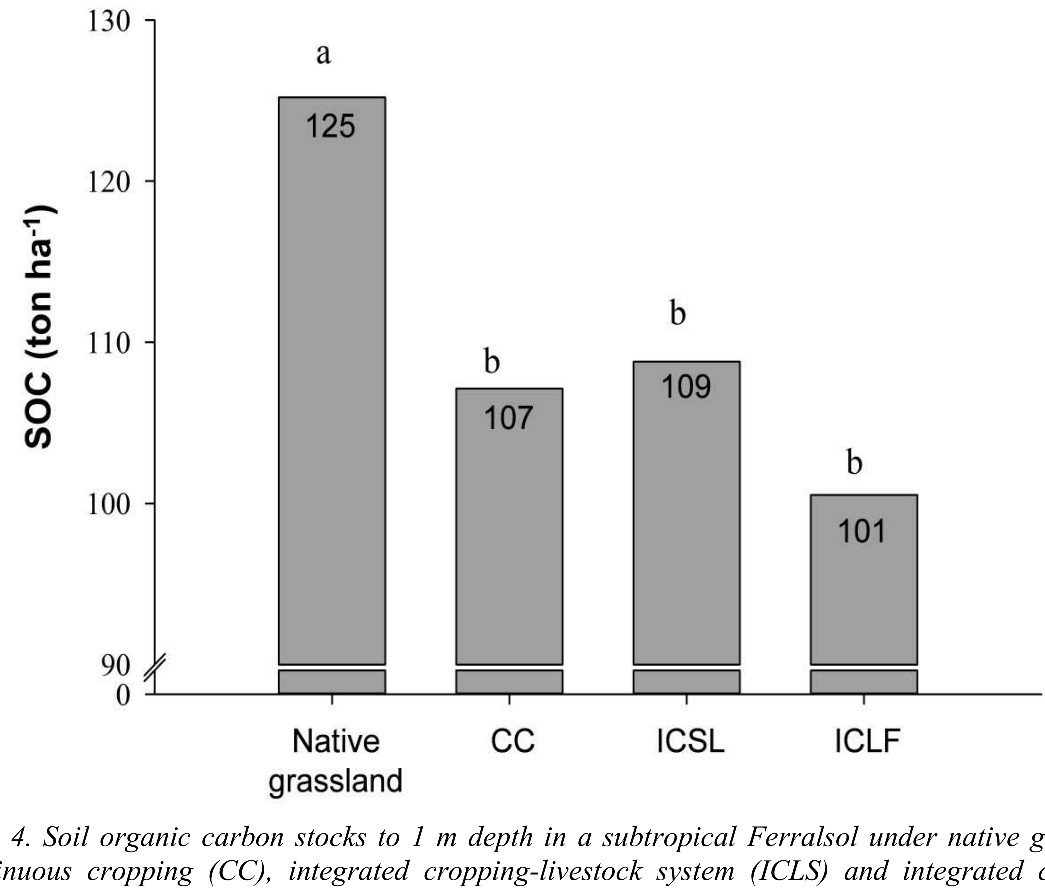

FIG. 4. Soil organic carbon stocks to 1 m depth in a subtropical Ferralsol under native grassland, continuous cropping (CC), integrated cropping-livestock system (ICLS) and integrated cropping-livestock-forest (ICLF). Except native grassland, all land use systems were under no-tillage and the crop sequence depicted. Ponta Grossa-PR, Brazil.

When DCD was sprayed onto the urine patch, the N_2O fluxes and their peaks (Fig. 5), as well as the N_2O emission factor (Table 3), tended to be intermediate between those from application of urine only and of urine with DCD dissolved. However, significant reduction in the N_2O emission factor by spraying DCD occurred only in autumn (from 0.45 to 0.24%) ($P<0.05$), which was less than the reduces achieved with dissolved DCD (from 0.45 to 0.08%) (Table 3).

In dung patches, N_2O fluxes were considerably smaller than those from urine patches; including peak emissions (0.08–0.46 mg N m^{-2} h^{-1}), which were generally broader and not as clearly defined as those from urine (Fig. 6 and Fig. 5). Thereafter, N_2O fluxes returned to the background level 15–37 days after dung deposition, depending on the season (Fig. 6). Cumulative N_2O emissions ranged from 35 to 141 mg N m^{-2} $season^{-1}$, which was on average three times greater than those from the control soil but was only one-eighth of those from the urine patch (Table 3). The N_2O emission factor for dung averaged 0.11% across the four seasons, varying from 0.04 to 0.23% (Table 3).

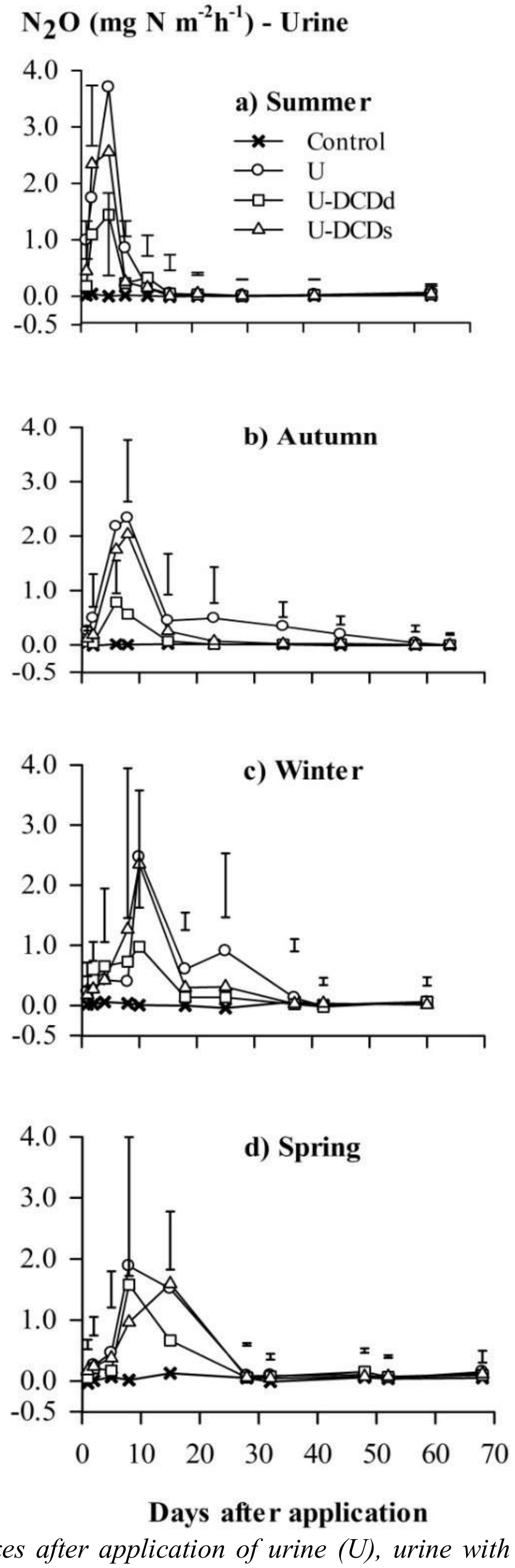

FIG. 5. Nitrous oxide fluxes after application of urine (U), urine with dicyandiamide dissolved (U-DCDd) and urine followed by dicyandiamide sprayed (U-DCDs) in the four evaluation seasons. Vertical bars are the LSD according to Tukey's test (P<0.05). Pinhais, Brazil.

TABLE 3. CUMULATIVE EMISSION AND EMISSION FACTOR OF N_2O AFTER APPLICATION OF URINE (U), DUNG (D), DICYANDIAMIDE DISSOLVED INTO URINE (U-DCDd) OR DUNG (D-DCDd), AND DICYANDIAMIDE SPRAYED ON URINE PATCH (U-DCDs) OR DUNG PAT (D-DCDs) IN THE FOUR EVALUATION SEASONS. PINHAIS, BRAZIL

Season	Control	U	U-DCDd	U-DCDs	D	D-DCDd	D-DCDs
Cumulative emission of N_2O (mg N m^{-2} $season^{-1}$)							
Summer	15 b A	489 a B	243 ab AB	362 a A	35 b A	39 b B	44 b A
Autumn	03 c A	791 a A	148 c B	430 b A	66 c A	70 c B	61 c A
Winter	24 c A	716 a A	302 b AB	555 a A	141 b A	44 c B	99 bc A
Spring	74 b A	727 a A	463 a A	607 a A	102 b A	185 b A	126 b A
Mean	29 c	681 a	289 b	489 ab	86 c	85 c	83 c
SED (±)	16	66	66	56	46	34	19
Emission factor of N_2O-N (%)							
Summer		0.19 a B	0.09 ab A	0.14 ab A	0.04 b	0.05 ab	0.06 ab
Autumn		0.45 a A	0.08 c A	0.24 b A	0.11 c	0.12 c	0.10 c
Winter		0.35 a A	0.14 b A	0.27 ab A	0.23 a	0.04 b	0.15 ab
Spring		0.35 a A	0.21 a A	0.28 a A	0.05 b	0.21 a	0.10 ab
Mean		0.34 a	0.13 b	0.23 ab	0.11 b	0.11 b	0.10 b
SED (±)		0.05	0.03	0.03	0.04	0.04	0.02

Probability (Cumulative N_2O): DCD: <0.001; Excreta: <0.001; Interaction: <0.001; SED: 43.4
Probability (EF) DCD: <0.001; Excreta: <0.001; Interaction: <0.001; SED: 0.03

Note: Means followed by the same lowercase letter within a row are not significantly different among excreta and DCD treatments, and means followed by the same uppercase letter within a column are not significantly different among seasons (Tukey's test, P< 0.05)

When DCD was dissolved in dung, the fluxes, the cumulative emissions and the emission factors of N_2O measured in summer and autumn did not change significantly from those obtained in the correspondingly untreated dung pats (Fig. 6 and Table 3). However, N_2O emissions in winter decreased in the dissolved DCD treatment, resulting in a lower emission factor of 0.04% compared to untreated dung (0.23%). In spring, an unexpectedly opposite trend was observed, with the emission factor being four times greater with dissolved DCD than in untreated dung (0.21 vs. 0.05%) (Fig. 6 and Table 3). Overall, the annual emission factor averaged across the four seasons was the same for dung with or without DCD dissolved (0.11%). When sprayed onto dung pats, DCD did not affect N_2O emissions, so that the mean annual emission factor of 0.10% was also similar to the 0.11% of untreated dung (Table 3).

3.2.2. Conclusions

Urine and dung deposited by cattle onto pasture soils of the subtropical region are indeed important sources of N_2O, with EF of 0.34% for urine and 0.11% for dung. These emission factors are not as high as the default 2% that the IPCC recommends for national GHG inventories, which suggests that this default value may need to be revised for the subtropical region. In addition, our study supports the disaggregation of the EF for urine and dung.

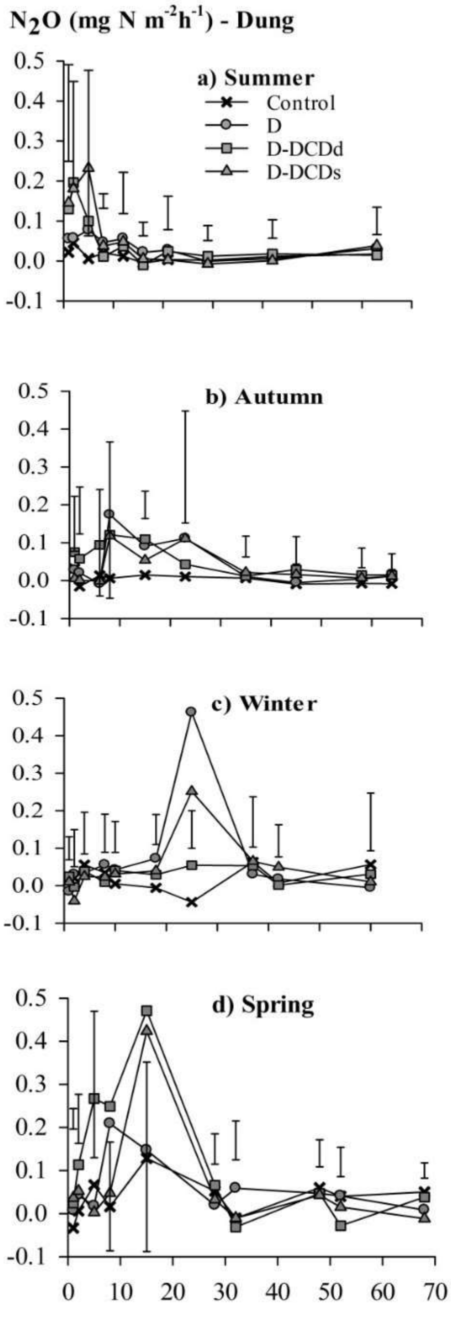

FIG. 6. Nitrous oxide fluxes after application of dung (D), dung with dicyandiamide dissolved (D-DCDd) and dung followed by dicyandiamide sprayed (D-DCDs) in the four evaluation seasons. Vertical bars are the LSD according to Tukey's test (P<0.05). Pinhais, Brazil.

As a mitigation strategy in subtropical pastures, the use of DCD has a potential to curb N_2O emission from urine patches, particularly in the cooler seasons of autumn and winter, when the emission decreased by 60–82% after being dissolved in urine. However, further testing of the application method of this nitrification inhibitor is needed to maximise its mitigation potential. Spraying, the most common application mode of DCD in pasturelands, has a limited effect in most of the seasons, except autumn, and was less efficient than when DCD was directly dissolved in urine. With respect to dung, there is no clear evidence that N_2O emission is mitigated with dicyandiamide, either dissolved into the dung mass or sprayed over the dung pat.

3.3. Experiment 3

3.3.1. Soil organic carbon (Castro site)

Soil organic carbon and total nitrogen concentration and stocks were not affected by ICLS relative to continuous cropping when soil was subjected to no-tillage (Table 4), in agreement with findings of the previous year in the Ponta Grossa experiment. There were no gains, but also no losses with ICLS. In other words, ICLS is efficient at maintaining the soil carbon and nitrogen stocks, which is welcomed considering all of the other known productive and economic benefits of ICLS.

However, in circumstances where soil is subjected to conventional tillage, results suggest that ICLS can at least enhance carbon and nitrogen stocks relative to continuous cropping, particularly below 20 cm depth (Table 4). Here, possibly ICLS partially abates the degrading condition of the conventional tillage system. However, it does not mean that conventional tillage combined with ICLS is a sustainable farming system, but rather that ICLS can make conventional tillage less harmful. For sustainable farming systems for this subtropical region, ICLS undoubtedly has to be based on no-tillage.

Accordingly, carbon and nitrogen sequestration rates over the nine years of ICLS were nil when under no-tillage but reached 1.13 t C ha^{-1} yr^{-1} and 0.08 t N ha^{-1} yr^{-1} under conventional tillage (Table 5).

With respect to soil carbon and nitrogen in physical fractions of the 0–5 cm layer, again no effect of ICLS was observed (Table 6). Our hypothesis was that carbon and nitrogen could increase in ICLS at least in the sand-POM fraction, but neither was confirmed. Free radical semiquinone concentration, which provides some qualitative information of the soil organic matter, did not change under ICLS (Table 6). In spite of the lack of effects, it continues to be seen as a positive argument for ICLS, as there was no sign of organic matter degradation and, as stated, ICLS has many productive and economic benefits.

3.3.2. Conclusions

Soil organic C and total N concentration and stocks were not influenced by ICLS compared to continuous cropping system. However, under conventional tillage, results suggest that ICLS have the most potential to enhance C and N suggesting practicing ICLS with no-tillage.

3.4. Experiment 4

3.4.1. Soil N_2O and CH_4 emission (Pinhais site)

During most of the evaluation period, N_2O fluxes were similar among treatments, generally with values lower than 100 μg N m^{-2} h^{-1} (Fig. 7a). However, emission peaks occurred after nitrogen application, being the most prominent in the pasture system, with values of 258, 118 and 2341 μg N m^{-2} h^{-1} after 1, 14 and 6 days after nitrogen fertilization in the summer-1, winter-1 and summer-2, respectively. The ICLS and ICLF systems showed similar fluxes, but were intermediate compared with the lower values in continuous cropping and with the higher values in pasture. The CH_4 fluxes were negative for most of the monitoring period for all systems, but without any clear effect of treatments (Fig. 7b). Some influx peaks occurred for ICLS and ICLF systems, with values close to –50 μg C m^{-2} h^{-1}.

TABLE 4. CONCENTRATION AND STOCKS OF SOIL ORGANIC CARBON (SOC) AND TOTAL NITROGEN (TN), AND BULK DENSITY OF A SUBTROPICAL FERRALSOL AFTER 9 YEARS UNDER CONTINUOUS CROPPING OR INTEGRATED CROPPING-LIVESTOCK SYSTEM (ICLS) COMBINED WITH CONVENTIONAL TILLAGE OR NO-TILL. CASTRO-PR, BRAZIL (24° 47′ 53″ S AND 49° 57′ 43″ W)

Layer (cm)	Cropland				ICLS			
	Conventional		No-tillage		Conventional		No-tillage	
SOC (g kg^{-1})								
0–5	30.0	Ba	37.5	Aa	28.6	Ba	38.3	Aa
5–10	30.2	Aa	29.5	Aa	27.5	Ab	30.0	Aa
10–20	27.0	Aa	26.3	Aa	28.2	Aa	27.1	Aa
20–30	23.0	Aa	24.4	Aa	24.0	Aa	21.7	Bb
30–45	18.5	Ab	20.1	Aa	20.7	Aa	20.1	Aa
45–60	15.4	Aa	17.1	Aa	17.0	Aa	17.4	Aa
60–80	13.8	Ba	16.0	Aa	15.1	Ba	16.1	Aa
80–100	13.3	Aa	14.0	Aa	13.5	Aa	13.5	Aa
SOC stock (t ha^{-1})								
0–20	62.7	Ba	65.0	Aa	61.7	Ba	66.2	Aa
0–100	199.3	Bb	212.9	Aa	209.5	Aa	209.5	Aa
TN (g kg^{-1})								
0–5	2.18	Ba	2.96	Aa	1.94	Bb	3.00	Aa
5–10	2.16	Aa	2.20	Aa	2.00	Bb	2.24	Aa
10–20	1.87	Aa	1.78	Ba	2.00	Aa	1.83	Ba
20–30	1.43	Ba	1.50	Aa	1.54	Aa	1.36	Bb
30–45	1.08	Bb	1.18	Aa	1.23	Aa	1.17	Aa
45–60	0.85	Aa	0.96	Aa	0.97	Aa	0.99	Aa
60–80	0.73	Bb	0.87	Aa	0.81	Aa	0.83	Aa
80–100	0.69	Aa	0.74	Aa	0.72	Aa	0.71	Aa
TN stock (t ha^{-1})								
0–20	4.40	Ba	4.70	Aa	4.40	Ba	4.80	Aa
0–100	12.10	Bb	13.00	Aa	12.80	Aa	12.80	Aa
Bulk density (kg dm^{-3})								
0–5	0.92	Aa	0.93	Aa	0.93	Aa	0.86	Aa
5–10	1.19	Aa	1.22	Aa	1.27	Aa	1.20	Aa
10-20	1.15	Aa	1.12	Aa	1.17	Aa	1.13	Aa
20–30	1.14	Aa	1.18	Aa	1.17	Aa	1.12	Aa
30–45	1.13	Aa	0.96	Ba	1.07	Aa	0.99	Ba
45–60	1.04	Aa	0.98	Ba	1.00	Aa	0.97	Ba
60–80	1.02	Aa	0.94	Ba	0.99	Aa	0.92	Ba
80–100	1.02	Aa	0.99	Aa	1.02	Aa	1.01	Aa

Note: capital letters in rows compare tillage systems, within the same soil use system; while lower case letters compare soil use systems, within the same tillage system (Tukey test, $p \leq 0.10$)

TABLE 5. TOTAL ORGANIC CARBON (TOC) SEQUESTRATION AND TOTAL NITROGEN (TN) ACCUMULATION RATES IN 0-20 CM AND 0-100 CM OF A SUBTROPICAL FERRALSOL AFTER 9 YEARS UNDER CONTINUOUS CROPPING OR INTEGRATED CROPPING-LIVESTOCK SYSTEM (ICLS) COMBINED WITH CONVENTIONAL TILLAGE OR NO-TILLAGE. CASTRO-PR, BRAZIL

Layer (cm)	ICLS (relative to continuous cropping)		No-tillage (relative to CT)	
	Conventional	No-tillage	Cropland	ICLS
SOC sequestration (t ha^{-1} yr^{-1})				
0–20	–0.11 ns	0.13 ns	0.26 *	0.52 *
0–100	1.13 *	–0.38 ns	1.51 *	0.00 ns
TN accumulation (t ha^{-1} yr^{-1})				
0–20	0.00 ns	0.01 ns	0.03 *	0.04 *
0–100	0.08 *	–0.02 ns	0.10 *	0.00 ns

Notes: * denotes significant rate and "ns" denotes not significant (Tukey test, p≤0.10). The SOC and NT sequestration rates were calculated for two situations. Firstly, for no-tillage, relative to the baseline conventional tillage, either considering the continuous cropping system or the ICLS; secondly, for ICLS, relative to the baseline cropping system, either considering the conventional or the no-tillage; in both cases considering 9 years.

TABLE 6. CONCENTRATION OF SOIL ORGANIC CARBON (SOC) AND TOTAL NITROGEN (TN), C:N RATIO AND MASS RECOVERY OF PHYSICAL GRANULOMETRIC FRACTIONS OF THE 0-5 CM LAYER OF A SUBTROPICAL FERRALSOL AFTER 9 YEARS UNDER CONTINUOUS CROPPING OR INTEGRATED CROPPING-LIVESTOCK SYSTEM (ICLS) COMBINED WITH CONVENTIONAL TILLAGE OR NO-TILLAGE. CASTRO-PR, BRAZIL

Physical fraction	Cropland		ICLS	
	Conventional	No-tillage	Conventional	No-tillage
SOC (g kg^{-1} fraction)				
Sand-POM	10.8	19.0	10.6	18.2
Silt	33.6	41.3	34.8	40.4
Clay	44.2	51.0	44.2	51.5
Bulk soil	30.0	37.5	28.6	38.3
TN (g kg^{-1} fraction)				
Sand-POM	0.80	1.45	0.87	1.36
Silt	1.96	2.72	2.18	2.61
Clay	3.39	4.27	3.58	4.27
Bulk soil	2.18	2.96	1.94	3.00
C:N ratio				
Sand-POM	13.5	13.1	12.1	13.4
Silt	17.2	15.2	15.9	15.5
Clay	13.0	11.9	12.4	12.1
Bulk soil	13.8	12.7	14.7	12.8
Semiquinone in HF treated samples [spins (× 10^{17}) g^{-1} of C]				
Sand-POM [2]	8.29 [1]	6.76	5.68	5.01
Silt	14.23	10.15	11.77	11.30
Clay	5.70	5.23	5.45	4.98
Bulk soil	13.54	9.02	12.23	9.99

Note: Sand-POM, sand plus particulate organic matter (>53 µm); silt (2 – 53 µm); clay (< 2 µm)

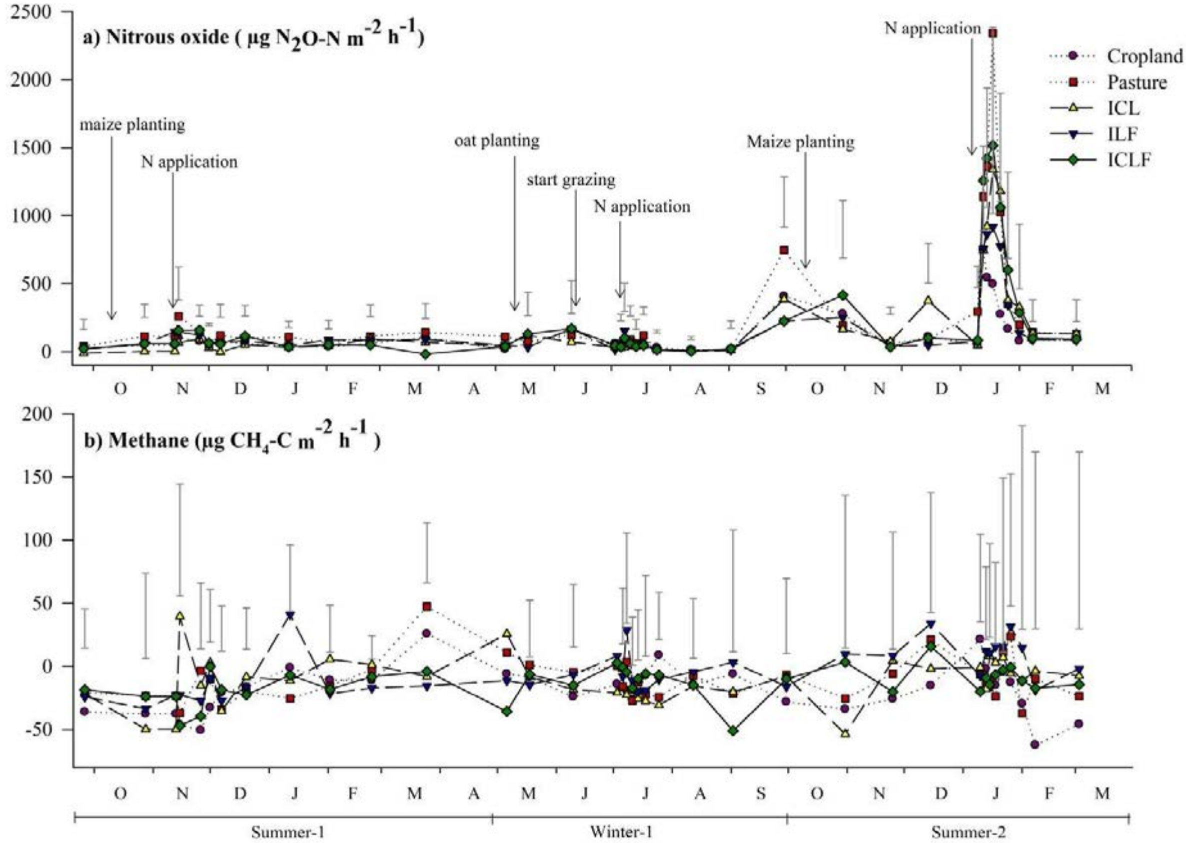

FIG. 7. Fluxes of nitrous oxide (a) and methane (b) from a subtropical Cambisol under continuous cropping, continuous pasture, integrated cropping-livestock (ICL), integrated cropping-livestock-forest (ICLF) and integrated livestock-forest (ILF). Pinhais-PR, Brazil.

With respect to the cumulative emissions, the pasture system emitted 23.17 kg N_2O-N ha^{-1} over the entire evaluation period, significantly higher than the other systems, which emitted about 13 kg N_2O-N ha^{-1} (Table 7). For CH_4, the influx did not differ between systems, with values close to 1 kg CH_4-C ha^{-1}.

The water filled pore space (WFPS) showed a similar trend in all systems, and the changes occurred according to rainfall conditions. In general, WFPS was between 40 and 80% (Fig. 8a), with values close to 100% during periods of frequent rainfall. The soil temperature followed the temporal variations of each season of the year but was not significantly different among treatments (Fig. 8b). The concentrations of soil ammonium and nitrate were higher soon after the nitrogen fertilization events, with subsequent reduction of the concentration (Fig. 9). The systems presented similar behaviours, with no significant difference among them. The concentration of ammonium in the soil reached maximum values of 220 and 241 mg NH_4^+-N ha^{-1} after summer fertilization (2016/17) and winter (2017), while NO_3^- concentration in the soil reached values of 175 and 72 mg NO_3^--N ha^{-1} for the same period.

TABLE 7. CUMULATIVE EMISSIONS OF NITROUS OXIDE AND METHANE DURING 526 DAYS FROM A SUBTROPICAL CAMBISOL UNDER CONTINUOUS CROPPING, CONTINUOUS PASTURE, INTEGRATED CROPPING-LIVESTOCK (ICLS), INTEGRATED CROPPING-LIVESTOCK-FOREST (ICLF) AND INTEGRATED LIVESTOCK-FOREST (ILF). PINHAIS-PR, BRAZIL

			Pasture		ICLS		ILF		ICLF	
N_2O (kg N_2O-N ha^{-1})	12.15	b	23.17	a	13.99	b	12.32	b	14.89	b
CH_4 (kg C-CH_4 ha^{-1})	–1.72	ns	–0.76		–1.47		–0.69		–1.68	
non-CO_2 (ton CO_2eq ha^{-1})	5.87	b	11.27	a	6.78	b	5.98	b	7.21	b

Note: Means followed by the same letter on the row are not significantly different, according to Tukey's test (P<0.05).

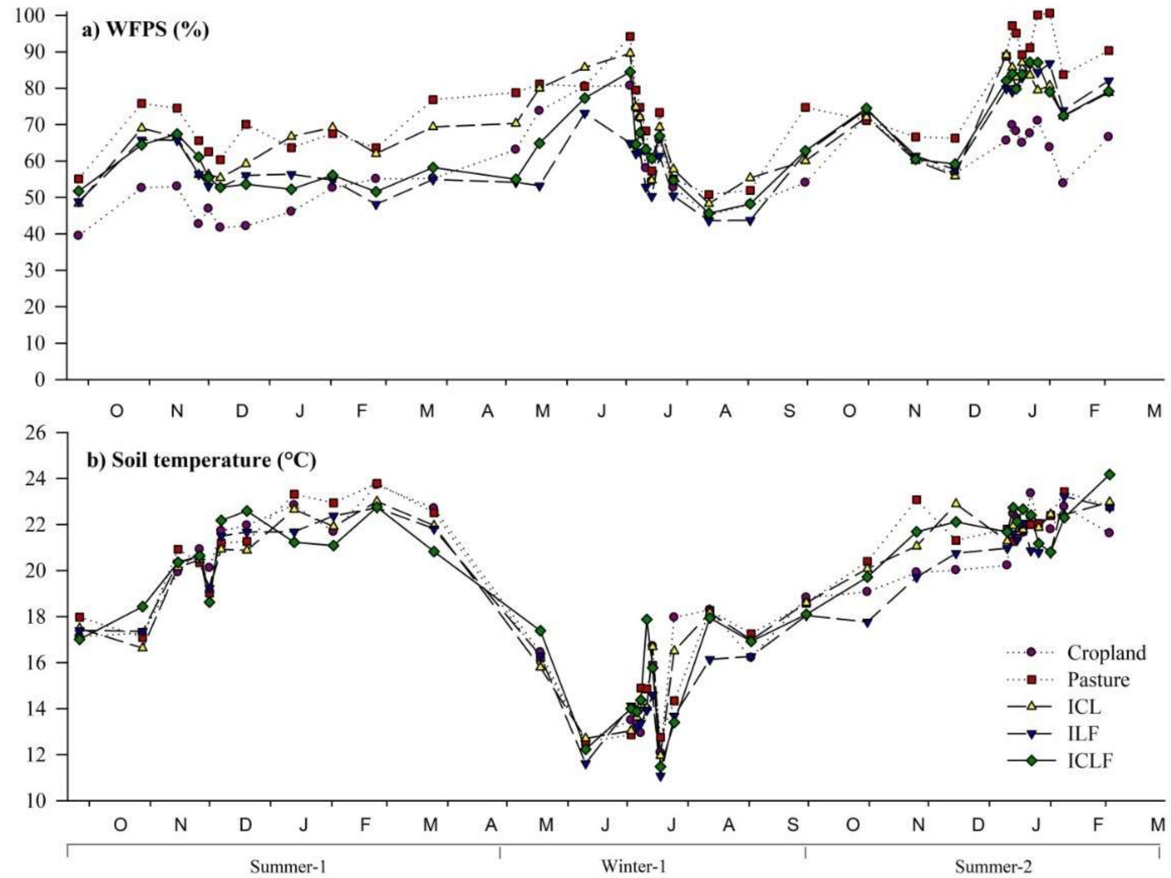

FIG. 8. Water filled pore space (WFPS, a) and temperature (b) of a subtropical Cambisol under continuous cropping, continuous pasture, integrated cropping-livestock (ICL), integrated cropping-livestock-forest (ICLF) and integrated livestock-forest (ILF). Pinhais-PR, Brazil.

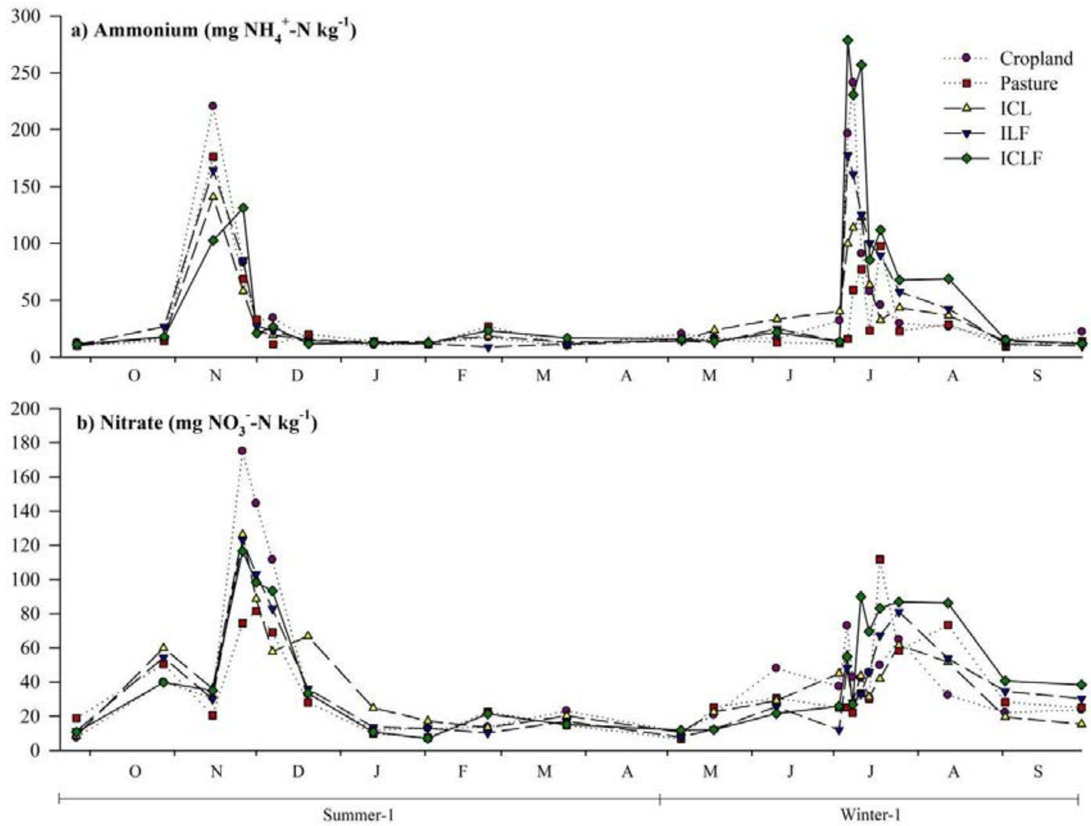

FIG. 9. Ammonium (a) and nitrate (b) concentrations in the 0-5 cm layer of a subtropical Cambisol under continuous cropping, continuous pasture, integrated cropping-livestock (ICLS), integrated cropping-livestock-forest (ICLF) and integrated livestock-forest (ILF). Pinhais-PR, Brazil.

3.4.2. Conclusions

Pasture was the system that emitted most N_2O to the atmosphere from the soil in relation to continuous cropping, ICLS, ICLF and ILF systems; possibly due to the higher soil density of the surface layer due to the constant presence of animals in the area, providing physical conditions for a longer retention of water in the soil pores. Relative to pasture, integrated systems emitted less N_2O, thus affording potential for mitigation of GHG emissions.

4. OVERALL CONCLUSIONS

Integrated farming systems, like crop-livestock or crop-livestock-forest, do have potential to reduce soil N_2O emission relative to continuous cropping or continuous pasture in subtropical environments, but the underlying cause of that reduction needs to be better understood. However, no effect of integrated farming was observed on soil CH_4 emissions and on SOC stocks or fractions. This shows that there is no negative effect of integrated systems and its grazing on soil carbon, while also not compromising other productive and economic advantages of this system.

In regard to the nitrous oxide emission factor of urine and dung deposited by cattle onto pasture soils, the values of 0.34% for urine and 0.11% for dung are not as high as the default 2% that the IPCC recommend for national GHG inventories, which suggests that this default value may need to be revised for the subtropical region. Additionally, the use of the nitrification inhibitor DCD has a potential to curb N_2O emission from urine patches, particularly in the cooler seasons of autumn and winter.

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OPTIMIZING SOIL, WATER AND NUTRIENT USE EFFICIENCY IN INTEGRATED CROPPING–LIVESTOCK PRODUCTION SYSTEM IN SOUTHERN INDIA

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Abstract

Organic carbon and nitrogen content in soil increased, even without external application of fertilisers in all the experimental fields recycled with dung and urine, indicating soil nutrient use efficiency. Incorporation of organic sources viz., farmyard manure and inorganic phosphorus and potassium helped in the rapid decomposition of manure, and higher microbial activity in turn resulted in high microbial biomass. Introducing the SRI (System of Rice Intensification developed by Tamil Nadu Agricultural University, India) cultivation of rice and drip irrigation in green fodder cultivation led to water use efficiency, with the input of water for every kg production of crop and green fodder being reduced. Replacing inorganic nitrogen with farmyard manure along with inorganic phosphorus and potassium in SRI cultivation, maintained yield as well as soil fertility. Thus, integrated nutrient management maintains post-harvest soil fertility without deteriorating the natural resource base for future use. By feeding the fodder grown in the nutrient recycled fields, the birth and weaning weights of calves increased by 20.5 and 10.5%, respectively. The adult weight, milk yield, and reproduction performance of dairy cattle likewise improved.

1. INTRODUCTION

The research project was carried out with the aim to preserve the soil nutrients *viz.,* nitrogen, phosphorus, potassium, and organic carbon through integrating crop (paddy) and fodder [Hybrid Napier (*Pennisetum perpureum* × *Pennisetum americanum*; VAR. Co(CN)4) and *Desmanthus virgatus*], with livestock (cows and goats). The scheme was implemented in different agro-climatic zones of Tamil Nadu, India, to assess the effective utilization of soil nutrients. The available land in TANUVAS institution and three private farmers was selected. Nine dairy cows and nine goats were selected. Based on the feed requirement for the livestock the crop residues and fodder were produced. Soil profiles were analysed from the experimental field before the study began. Paddy and perennial fodder crops were grown in the experimental fields. Standard management practices were adopted for the rice crop and fodders. The paddy straw was fed to cows but not to goats. Green fodder was fed to cows and goats. The quantity fed to the animals was recorded.

Animal excreta (dung and urine) were collected and measured while the animals were in their housings. The collected dung was stored and recycled to the same land where crop and fodder was grown for feeding the animals. Cows were allowed to graze after paddy was harvested and crop yield, crop residue yield, fodder yield, production, and reproduction parameters of animals integrated with the cropping system were recorded.

Soil nutrients were conserved through recycling of dung and urine. The production and reproduction performance of the animals were also enhanced by utilizing the organically produced crop residues and green fodder.

2. METHODOLOGY

2.1. Location of Experiments

One site was located on TANUVAS institutional land in the north-eastern agroclimatic zone (Kancheepuram) and three were located in private farmers' fields in the Cauvery delta zone (Trichy), western agroclimatic zone (Erode), and southern agroclimatic zone (Madurai) of Tamil Nadu. The land area selected for cultivation of crop and green fodder at each location is given in Table 1. Paddy was cultivated every year. Perennial fodder Hybrid Napier and leguminous fodder *Desmanthus virgatus* were also cultivated for feeding animals. Nine dairy cows and nine goats were selected to study the production / reproduction performance of the animals at the different locations (Table 1).

TABLE 1. LOCATION OF EXPERIMENTS, AREAS AND TYPES OF GRAIN AND FODDER CROPS AND TYPES AND NUMBERS OF LIVESTOCK

Location	Crops		Fodder		Livestock	
	Type	Area (ha)	Type	Area (ha)	Dairy cattle	Goat
TANUVAS[a]	Rice	1.10	Hybrid Napier[b]	0.445	9 (3 × 3 reps)	9 (3 × 3 reps)
			Desmanthus virgatus[c]	0.486		
Cauvery delta region		1.21	Hybrid Napier[b]	0.364	3	3
			Desmanthus virgatus[c]			
Western region		1.62	Hybrid Napier[b]	0.162	3	3
			Desmanthus virgatus[c]	0.607		
Southern region		1.82	Hybrid Napier[b]	0.81	3	3
			Desmanthus virgatus[c]	0.404		

Note: [a] **Tamil Nadu Veterinary and Animal Sciences University land, north eastern zone**
[b] **Perennial grass**
[c] **Legume**

2.2. Soil Sampling

Initial soil samples were collected from the respective fields by using the following procedure. Five samples from each field were collected. The samples were shade dried, mixed thoroughly and unwanted materials like roots, stones, pebbles, and gravel were removed. The clods in the samples were broken using a wooden mallet and then crushed to pass through a 2 mm sieve.

After that the sample size was reduced to 0.5 kg by dividing the thoroughly mixed sample into four equal parts. The two opposite quarters were discarded and the remaining two quarters were remixed and the process repeated until the desired sample size was obtained. The samples were stored in polythene bags for analysis. Paddy field soil samples were collected before cultivation and after harvest. Soil samples under Hybrid Napier and *Desmanthus virgatus* were collected during January and July every year.

2.3. Paddy Cultivation

The areas of paddy rice planted in the different regions are given in Table 1. The ADT 43 variety of paddy was selected for cultivation. The rice seeds were nursery sown and 14 day old seedlings were transplanted 25 × 25 cm apart. Rice was mainly watered by irrigating through flood irrigation. To save water, rice was irrigated after formation of hairline cracks in the soil. i.e. alternate wetting and drying. Maximum water depth was maintained at 2.5 cm up to the panicle initiation stage. The farms were flooded to the same depth thereafter until harvest. On average, 53% less irrigation water was used in SRI farms. The paddy was harvested on the 120th day by machine harvest. The collected seeds and straw were weighed in the field. The straw was collected from three replications and weighed and stored separately and marked with three colours to feed the respective animals. Paddy straw was collected after harvest for proximate analysis.

2.4. Fodder Cultivation

The areas of Hybrid Napier grass and *Desmanthus virgatus* planted in the different regions are given in Table 1. Napier grass [Cumbu hybrid Co(CN)4] and *Desmanthus virgatus* plots were cultivated by ploughing and the ridges and furrows were formed by 60 cm × 60 cm. Hybrid Napier was established by using stem cuttings and *Desmanthus virgatus* from seed. Farmyard manure was applied as basal manure. A top dressing of urea was applied on the 30th day and was repeated after each cutting. The first cut was made at 75 days after planting and subsequent harvests at 45-day intervals thereafter. The yield of fodder was recorded for every cut. The field was separated into three replications, each identified with three different colours to feed the respective replication of the animal. Fodder crops were either drip or furrow irrigated. Hybrid Napier and *Desmanthus virgatus* samples were collected every six months from the field and for proximate analysis.

2.5. Grazing of Animals in the Harvested Paddy Field

Dairy cattle were allowed to graze the paddy the day after harvest until the onset of the monsoons. Goats were never fed with paddy straw and were not allowed to graze on the paddy. During this trial period the feed requirement was calculated as below and the green fodder was offered as per the requirement.

2.6. Feeding of Animals

Fodder requirement was calculated on the basis of the body weight of the animal. It was recommended on a dry matter basis (Table 2).

TABLE 2. FODDER REQUIREMENT OF ANIMALS

Fodder type	Fodder amount (kg)	
	Dairy cow	Sheep and goat
Paddy straw	2.5 – 5	Feeding dry roughage is not adopted
Napier hybrid grass	15 – 22	3.75 – 5
Desmanthus virgatus	5 – 7	1.25 – 1.75

The cattle and goats were respectively fed with 3% and 6% of dry matter according to their body weight. All experimental dairy cows were fed with 66.6% of dry matter as roughage (44.4% Hybrid Napier grass and 22.2% *Desmanthus virgatus* leguminous fodder) and 33.3% as concentrate feed. The concentrate feed contained 16% crude protein and 70% TDN.

2.7. Use of Dung and Urine

Every day the dung voided from dairy cattle and goats was collected and stored in heaps for 5 months, during which time the dung composted and became farmyard manure. This manure was applied to the fields of paddy and fodder cultivation. The farmyard manure was utilised in the place of urea and was a cost-saving measure. Likewise, the urine voided from the cattle partially replaced urea as a nitrogen source. The incidence of disease was reduced in the paddy and fodder cultivation due to the ammoniacal smell of urine that restricted the entry of pests.

2.8. Production and Reproduction Performance of Animals

The production performance of dairy cows was recorded by weighing all the animals every month, documenting their milk production (l day^{-1}), and recording the number of calves born per year along with their birth weights. The reproduction performance of the cows was recorded by calving interval, number of services per conception, average days for first insemination, conception rate, and pregnancy rate. This was carried out from the beginning to the end of the project in all experimental regions.

The production performance of goats was recorded by weighing each animal every month, number of kids born, average birth weight, weaning weight at three months of age, and average adult weight. The reproduction performance of the goats was recorded by average age at first estrum, average age at first kidding, average number of full-term parturitions, average number of kids born live out of total kids born, kidding interval period, and post-partum heat period. This was carried out from the beginning to the end of the project in all experimental regions.

3. RESULTS AND DISCUSSION

3.1. Changes in Soil Properties under Paddy

The temporal changes in surface soil properties from the beginning to the end of the 5-year paddy cropping period are shown in Table 3 and Figs. 1 and 2.

Soil pH and electrical conductivity decreased after each harvest and further decreased at the end of project across all regions (Table 3). Usually soil pH increases after flooding and stabilizes around 50 days in all the soils as reported by Fageria et al. [1]. However due to the alternate flooding and drying method of irrigation in SRI cultivation there was a decreasing trend in pH over the years.

Trends in soil organic carbon of the paddy field were inconsistent between regions over the five years (Table 3). This might be due to the variable application of farmyard manure and incorporation of green manure before rice cultivation. The results of Goyal et al. [2] supported these findings. Therefore, in SRI cultivation, replacing of inorganic nitrogen with farmyard manure along with inorganic phosphorus and potassium can maintain yield as well as the fertility status of the soil. Thus, the results assume greater importance of integrated nutrient management in maintaining post-harvest soil fertility status of soil without deteriorating the natural resources for future use.

Available nitrogen decreased after each harvest and increased before the next sowing in all four agro-climatic zones. In Tamil Nadu, Sunhemp (*Crotolaria juncea*) green manure is cultivated every year before paddy and it is incorporated into the field before flowering. Increase in soil available nitrogen was recorded before cultivation of paddy due to the incorporation of green manure, and also after cultivation soil available nitrogen was reduced due to the nitrogen uptake by the plant. These results confirm the findings of Galitz [3]. Over the 5-year experimental period there was no consistency between regions in respect of changes in soil N (Table 3).

At the beginning of the experiment soil available phosphorus content was 15.5, 11.3, 11.8, and 15.8 kg ha^{-1} in north eastern, Cauvery Delta, western and southern zones, respectively. The available phosphorus (P) in the post-harvest soil increased in all the five zones indicating phosphorus-solubilizing capacity of green manures in maintaining soil available phosphorus [4]. However, over the 5-year experimental period there was no consistency between regions in changes in soil P (Table 3).

Similarly, available potassium (K) was also improved in post-harvest soil due to the incorporation of weeds by the ‘cone weeder’ once in 10 days in SRI cultivation which supported easy decomposition of mineral constituents and their effect in dislodging the exchangeable potassium into the soil solution [6]. However, over the 5-year experimental period there was no consistency between regions in changes in soil K (Table 3).

TABLE 3. MEAN (N = 6, ± SE) SURFACE SOIL PROPERTIES AT THE BEGINNING AND END OF THE FIVE-YEAR PADDY CROPPING PERIOD IN FOUR REGIONS

Region	Time (years)	pH	EC[a] (dS m^{-1})	Organic C (g kg^{-1})	Total nutrient (kg ha^{-1})		
					N	P	K
North east	0	7.2 ± 0.4	0.97 ± 0.05	1.8 ± 0.1	351 ± 18	15.5 ± 0.8	82 ± 4
	5	6.1 ± 0.3	0.22 ± 0.01	5.7 ± 0.3	301 ± 15	19.2 ± 1.0	113 ± 6
Delta	0	7.2 ± 0.4	0.65 ± 0.03	6.9 ± 0.4	190 ± 10	11.3 ± 0.6	153 ± 8
	5	6.2 ± 0.3	0.22 ± 0.01	5.3 ± 0.3	160 ± 8	7.1 ± 0.4	108 ± 6
West	0	7.1 ± 0.4	0.20 ± 0.01	6.8 ± 0.4	190 ± 10	11.8 ± 0.6	239 ± 12
	5	6.4 ± 0.3	0.02 ± 0.01	6.5 ± 0.3	252 ± 13	22.2 ± 1.2	124 ± 6
South	0	7.9 ± 0.4	0.64 ± 0.03	8.0 ± 0.4	189 ± 10	15.8 ± 0.8	223 ± 12
	5	6.6 ± 0.4	0.41 ± 0.02	6.6 ± 0.3	259 ± 14	11.5 ± 0.6	246 ± 13

Note:[a] EC, electrical conductivity

3.2. Changes in Soil Properties under Hybrid Napier

Changes in soil properties of the Hybrid Napier fields from the start to the end of the project are presented in the Table 4 and in Figs. 3 and 4. As seen for paddy, there was a consistent decrease across regions for soil pH and electrical conductivity, while trends in organic C, N, P and K were inconsistent across regions (Table 4), which might have been due to the variable application of farmyard manure during the cropping period as reported by Meena et al. [6]. Mean values across regions for organic C and K decreased (Figs. 3 and 4), P remained unchanged, while N increased (Fig. 3) over the five experimental years.

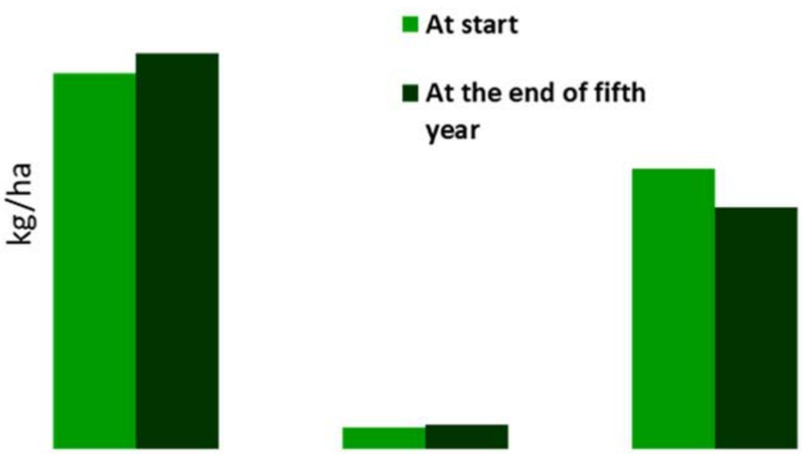

FIG. 1. Mean changes in the soil nutrient status (N, P, K) of the paddy fields over five years.

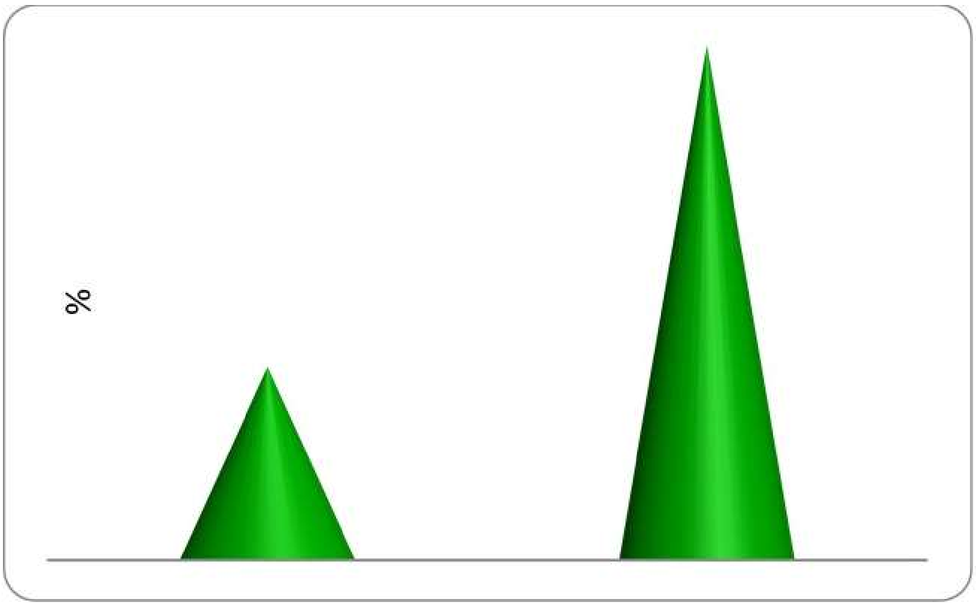

FIG. 2. Mean changes in soil organic C of the paddy fields over five years.

TABLE 4. MEAN (N = 6, ± SE) SURFACE SOIL PROPERTIES AT THE BEGINNING AND END OF THE FIVE-YEAR HYBRID NAPIER FORAGE PERIOD IN FOUR REGIONS

Region	Time (years)	pH	EC[a] (dS m^{-1})	Organic C (g kg^{-1})	Total nutrient (kg ha^{-1})		
					N	P	K
North east	0	7.5 ± 0.4	0.46 ± 0.02	2.2 ± 0.1	189 ± 0	10.5 ± 0.5	140 ± 7
	5	7.0 ± 0.4	0.03 ± 0.01	4.8 ± 0.2	252 ± 13	20.1 ± 1.1	83 ± 4
Delta	0	7.5 ± 0.4	0.45 ± 0.02	5.8 ± 0.3	189 ± 10	13.3 ± 0.7	185 ± 9
	5	6.8 ± 0.4	0.15 ± 0.01	4.2 ± 0.2	165 ± 9	5.5 ± 0.3	78 ± 4
West	0	7.1 ± 0.4	0.86 ± 0.04	8.2 ± 0.4	113 ± 6	18.5 ± 1.0	190 ± 10
	5	6.5 ± 0.3	0.04 ± 0.01	4.8 ± 0.3	162 ± 8	18.6 ± 1.0	92 ± 5
South	0	7.1 ± 0.4	0.94 ± 0.05	7.2 ± 0.4	161 ± 8	17.4 ± 0.9	186 ± 10
	5	6.3 ± 0.3	0.52 ± 0.03	5.6 ± 0.3	274 ± 14	11.5 ± 0.6	245 ± 13

Note: [a] EC, electrical conductivity

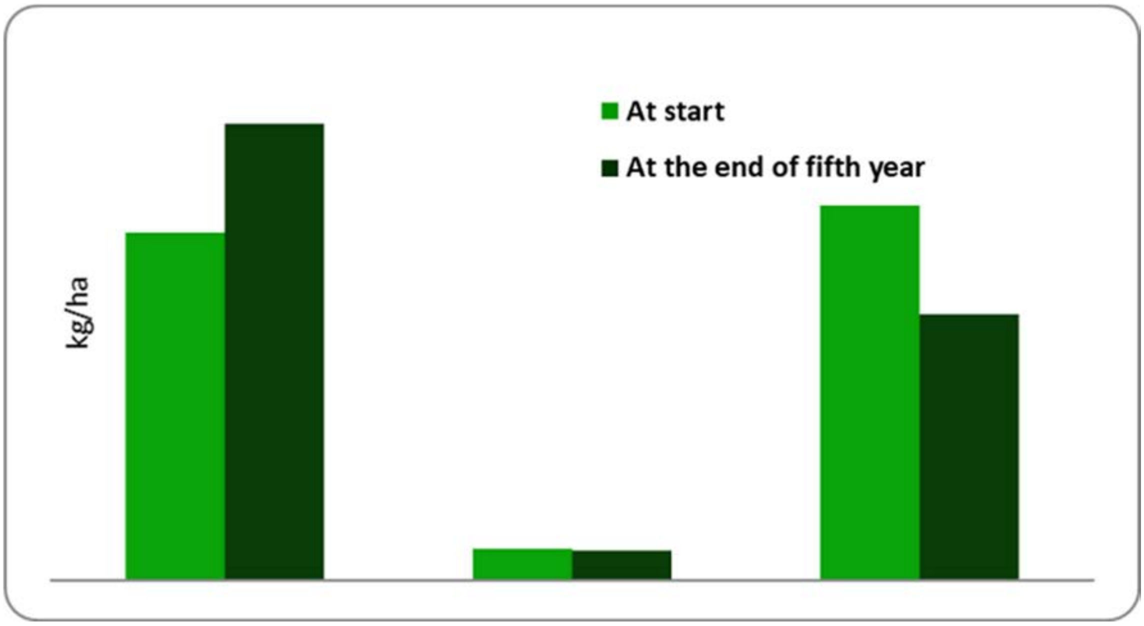

FIG. 3. Mean changes in the soil nutrient status (N, P, K) of the Hybrid Napier grass fields over five years.

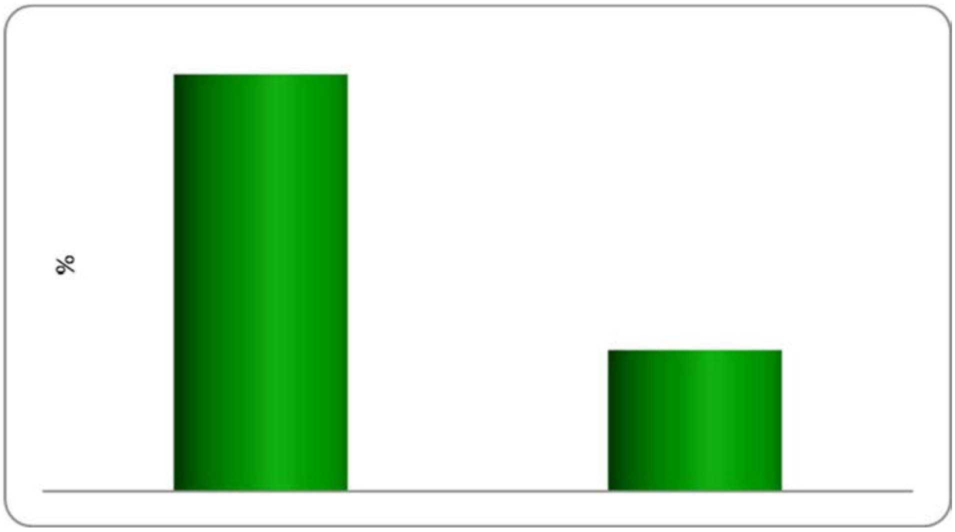

FIG. 4. Mean changes in soil organic C of the Hybrid Napier grass fields over five years.

3.3. Changes in Soil Properties under *Desmanthus Virgatus*

Changes in soil surface properties of the *Desmanthus virgatus* fields from the start to end of the project period are presented in Table 5 and in Figs. 5 and 6. Electrical conductivity decreased across all regions during the 5-year cropping period as also seen for paddy and Hybrid Napier. pH remained unchanged or decreased (Table 5), whereas trends in organic C, N, P, and K were inconsistent across regions, which may have been due to the variable application of organic fertilisers and also by biological N_2 fixation by *Desmanthus virgatus* [7]. Mean values for organic C, P, and K across regions decreased (Figs. 5 and 6), while N increased (Fig. 5).

TABLE 5. MEAN (N = 6, ± SE) SURFACE SOIL PROPERTIES AT THE BEGINNING AND END OF THE FIVE-YEAR *DESMANTHUS VIRGATUS* FORAGE PERIOD IN FOUR REGIONS

Region	Time (years)	pH	EC[a] (dS m^{-1})	Organic C (g kg^{-1})	Total nutrient (kg ha^{-1})		
					N	P	K
North east	0	6.9 ± 0.4	0.56 ± 0.03	4.6 ± 0.2	251 ± 13	11.7 ± 0.6	195 ± 10
	5	6.9 ± 0.4	0.04 ± 0.01	4.2 ± 0.2	258 ± 13	12.2 ± 0.6	118 ± 6
Delta	0	8.3 ± 0.4	0.83 ± 0.04	4.5 ± 0.2	214 ± 11	23.3 ± 1.2	280 ± 14
	5	6.5 ± 0.3	0.12 ± 0.01	2.2 ± 0.1	134 ± 7	7.9 ± 0.4	67 ± 3
West	0	8.0 ± 0.4	0.49 ± 0.03	2.4 ± 0.1	188 ± 10	19.3 ± 1.0	220 ± 11
	5	7.2 ± 0.4	0.02 ± 0.01	4.1 ± 0.2	251 ± 13	16.8 ± 0.9	148 ± 8
South	0	7.1 ± 0.4	0.84 ± 0.04	6.0 ± 0.3	201 ± 11	18.3 ± 1.0	239 ± 13
	5	6.3 ± 0.3	0.56 ± 0.03	6.5 ± 0.3	250 ± 13	9.2 ± 0.5	290 ± 15

Note: [a] EC, electrical conductivity

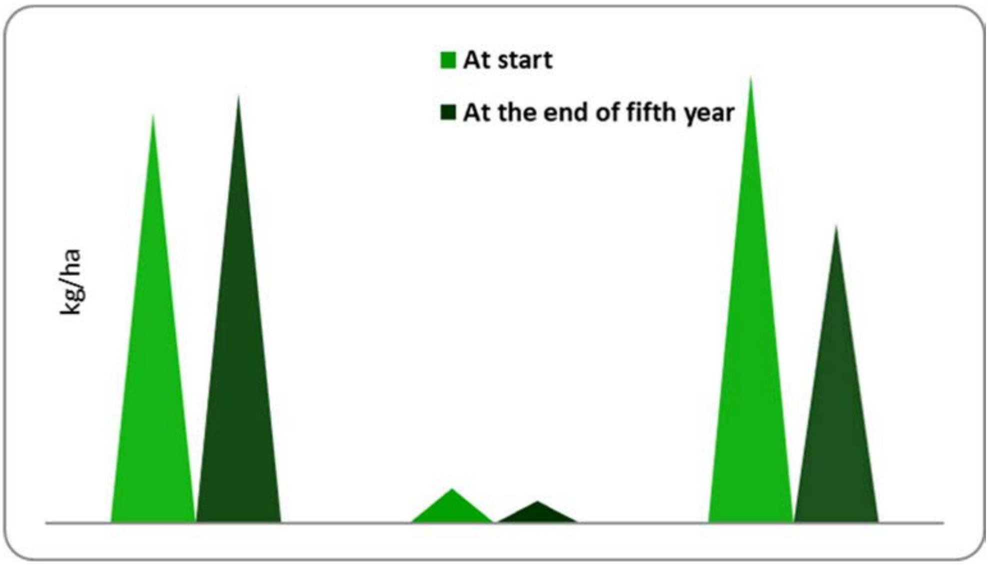

FIG. 5. Mean changes in the soil nutrient status (N, P, K) of the Desmanthus virgatus fields over five years.

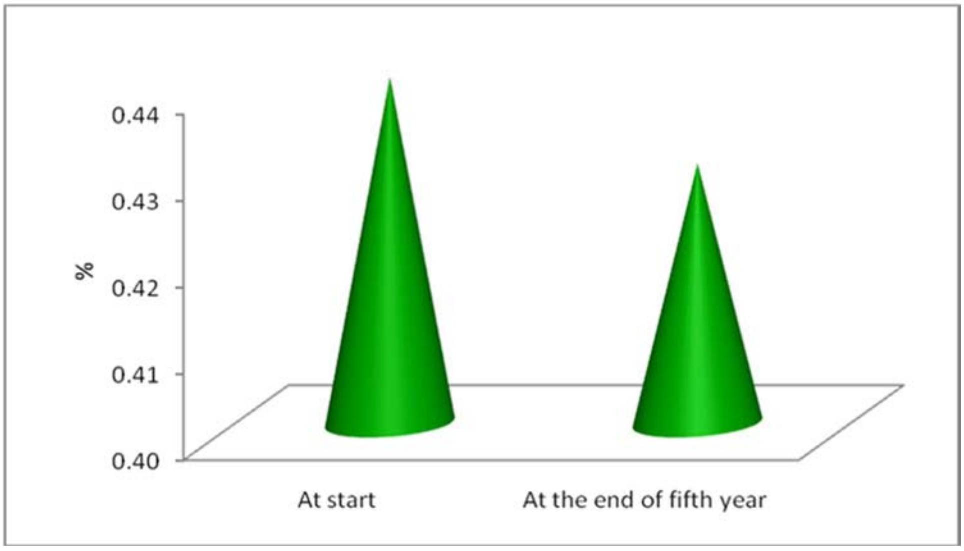

FIG. 6. Mean changes in soil organic C of the Desmanthus virgatus fields over five years.

3.4. Paddy and Straw Yields

Paddy and straw yields were recorded for the first and last of the five years in all four agro-climatic zones (Table 6 and Fig. 7).

TABLE 6. MEAN (N = 6, ± SE) PADDY AND STRAW YIELDS AT THE BEGINNING AND END OF THE FIVE-YEAR CROPPING PERIOD IN FOUR REGIONS

Region	Time (years)	Season	Variety	Duration (days)	Yield (t ha^{-1})	
					Paddy	Straw
North east	0	1	ADT 43	120	5.94 ± 0.30	2.01 ± 0.10
	5	1			4.87 ± 0.25	5.75 ± 0.35
Delta	0	1	Karnataka ponni	110	2.14 ± 0.11	3.33 ± 0.17
	5	1			5.00 ± 0.26	10.22 ± 0.58
West	0	1			6.25 ± 0.33	11.00 ± 0.58
	5	1			6.25 ± 0.33	13.43 ± 0.71
South	0	2			1.42 ± 0.07	4.17 ± 0.21
	5	2			7.26 ± 0.37	15.21 ± 0.78

In the north-eastern zone, the ADT 43 variety was used and in the other three agro-climatic zones the rice variety Karnataka ponni was used for cultivation. In all four agro climatic zones, mean rice and straw yields increased compared with the first year (Fig. 7) because of the recycling of animal wastes into the system.

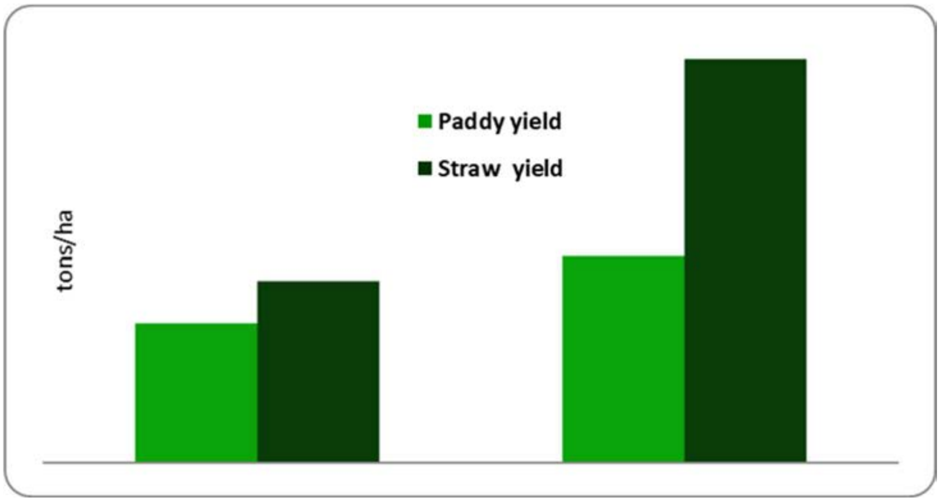

FIG. 7. Mean paddy and straw yields across regions at the beginning and end of the five- years cropping period.

3.5. Biomass Yields of Green Fodders

Biomass yields of green fodders at the beginning and end of the five-year period are presented in Table 7. Only farmyard manure was used for the nitrogen supplement instead of urea, although inorganic phosphorus and potassium were applied. Hybrid Napier yields increased in the northeast, remained stable in the west and fell in the Delta and southern regions, while *D. virgatus* yields increased in all regions.

3.6. Water Use Efficiency

The quantity of water utilized for paddy and green fodder for five years in four regions is presented in Table 7.

TABLE 7. MEAN (N = 6, ± SE) GREEN FODDER YIELDS AT THE BEGINNING AND END OF THE FIVE-YEAR CROPPING PERIOD IN FOUR REGIONS

Region	Time (years)	Number of cuttings		Biomass yield (t ha^{-1})	
		Hybrid	*D. virgatus*	Hybrid	*D. virgatus*
North east	0	8	7	228 ± 11	55 ± 3
	5	8	7	253 ± 13	74 ± 4
Delta	0	8	7	280 ± 14	42 ± 2
	5	6	7	211 ± 11	79 ± 4
West	0	7	7	225 ± 12	100 ± 5
	5	7	8	213 ± 11	133 ± 7
South	0	8	8	210 ± 11	18 ± 1
	5	6	8	105 ± 5	66 ± 3

TABLE 8. WATER UTILIZATION FOR PADDY AND FORAGES DURING FIVE YEARS IN FOUR REGIONS

Region	Time (years)	Paddy[a]	Forages	Water utilized ($l\ kg^{-1}$)[b]	
		Cultivation	Drip irrigation	Paddy	Forages
North east	0	-	No	-	50
	5	SRI	Yes	2500 (37.5)	39 (23)
Delta	0	Conventional	No	4000	55
	5	SRI	Yes	2500 (37.5)	55 (38)
West	0	Conventional	No	4000	55
	5	SRI	No	2500 (37.5)	70
South	0	Conventional	No	4000	60
	5	SRI	No	2500 (37.5)	75

Note: [a] **SRI, system of rice intensification (water and nutrient use efficiency method)**
[b] **Data in parentheses are water savings (%)**

The alternate wetting and drying method of irrigation saves water in rice cultivation. Optimum supply of irrigation water with mechanical weeding resulted in higher nutrient availability as reported by Pandian et al. [8].

3.7. Impact of Soil Nutrient and Water Utilized

The data on the impact of soil nutrient utilized (%) and water utilized (%) are presented in Figs. 8 and 9.

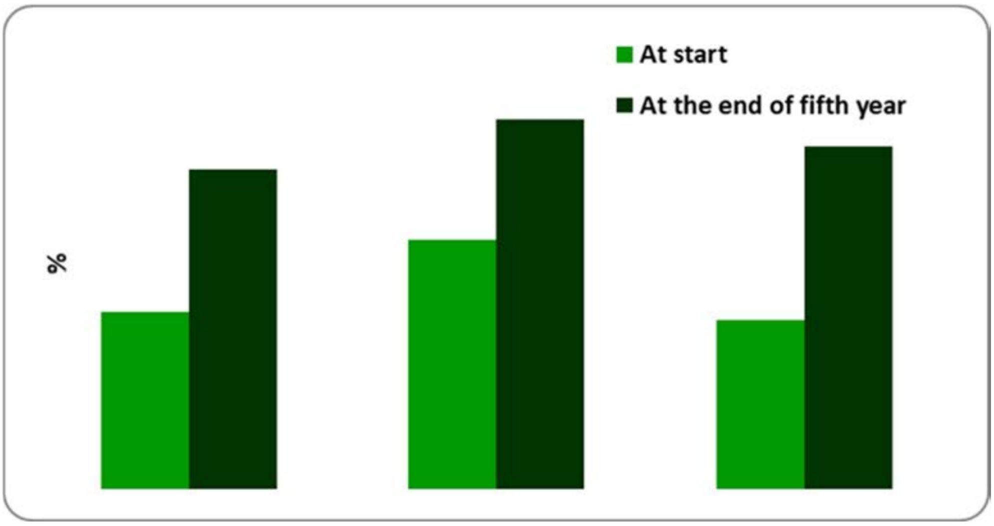

FIG. 8. Mean soil nutrients utilized (%) for paddy and green fodder over five years.

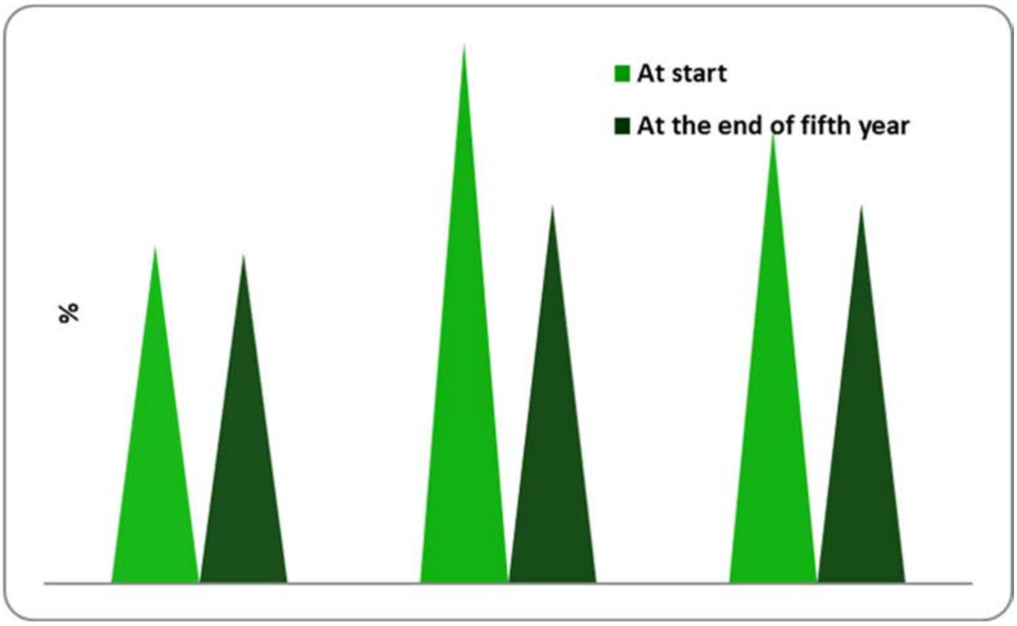

FIG. 9. Mean water utilized (%) for paddy and green fodder over 5 years.

The nutrients were supplied according to the need of the crop through recycling of animal manures and were utilized efficiently. The low nutrient use efficiency at the start might be due to crop uptake increasing as the nutrient dosage increases. The increase in water utilized was mainly due to considerable saving of irrigation water, greater increase in yield of crops and higher nutrient use efficiency [9].

3.8. Composition of Feed Concentrate, Paddy Straw, Hybrid Napier Grass and Desmanthus Virgatus

The nutrient composition of concentrate feed, paddy straw, Hybrid Napier grass and *Desmanthus virgatus* are presented in Table 9. Concentrate had the highest crude protein composition and the lowest crude fibre. All materials had similar N-free extracts of approximately 50% (Table 9).

TABLE 9. MEAN (N = 6, ± SE) PROXIMATE COMPOSITION IN FEED CONCENTRATE, HYBRID NAPIER GRASS, *DESMANTHUS VIRGATUS* AND PADDY STRAW

Fraction	Composition (%)			
	Concentrate	Hybrid	*D. virgatus*	Paddy straw
Crude protein	16.1 ± 1.2	7.6 ± 1.0	13.2 ± 1.1	4.9 ± 0.3
Ether extract	2.5 ± 0.15	2.0 ± 0.2	2.8 ± 0.2	1.25 ± 0.15
Crude fibre	10.7 ± 0.5	30 ± 2	20.4 ± 1.2	27.5 ± 0.8
Total ash	11.9 ± 1.0	11.9 ± 1.0	12.5 ± 0.5	17.5 ± 0.15
N-free extract	47 ± 2	48 ± 2.0	51 ± 1.0	49 ± 4

3.9. Cost Savings Through Use of Dung and Urine

The estimated cost savings through use of dung and urine are presented in Table 10.

TABLE 10. COST SAVINGS THROUGH USE OF DUNG AND URINE

Field	Area (ha)	Dung required (t)	Urea saved (kg)	Dung used (t)	Urine used (l wk^{-1})	Annual saving (Rs)
Paddy	14.0	49	735	50	-	4410
Hybrid Napier	4.4	32	2676	25	12.5	16056
D. virgatus	4.6	23	2041	20	16.0	17496
Cost of savings from insecticides						5000
Total savings per year						42962
Total savings for 5 years						214810

The farmyard manure utilization through the crop-livestock integrated system for paddy and fodder cultivation reduced the utilization of fertiliser and also increased the savings. Ashiono et al. [10] reported that farmyard manure was effective in maintaining the soil quality under continuous cultivation and led to higher crop yields.

3.10. Production Performance of Dairy Cattle

The production and reproduction performance of dairy cattle during the project period of five years at all experimental agro-climatic zones are presented in Table 11.

The body weight of the cattle significantly ($p<0.01$) increased at the end of the fifth year in all experimental agro-climatic zones. Similarly, the milk yield significantly ($p<0.01$) increased at the end of the fifth year in all experimental regions. The milk yield increased due to the feeding of concentrates and roughages with good quality green fodders such as leguminous fodder and non-leguminous fodder according to the nutrient requirement of the cattle. The concentrate feed and roughage were fed according to the body weight and milk yield with a given milk fat content. It was found that proper housing and feeding is required to ensure proper animal health in order to increase productivity [11]. Garg et al. [12] reported that the feeding of a nutritionally balanced ration increases the milk production of cattle.

TABLE 11. PRODUCTION PERFORMANCE (MEAN ± SE) OF DAIRY CATTLE AT THE BEGINNING AND END OF THE FIVE-YEAR PERIOD IN FOUR REGIONS

Region	Time (years)	Average body weight (kg)[a]	Average milk yield (l $animal^{-1}$)[a]	Calves born	Average[b] weight (kg)	
					Birth	Weaning
North east	0	302 ± 13	931 ± 15	4	20 ± 2	65 ± 4
	5	319 ± 20	941 ± 26	25	25 ± 2	77 ± 5
Delta	0	305 ± 25	997 ± 18	2	19 ± 2	80 ± 5
	5	352 ± 11	1228 ± 26	8	23 ± 2	94 ± 6
West	0	310 ± 16	786 ± 24	1	38 ± 2	92 ± 5
	5	353 ± 15	929 ± 18	11	45 ± 2	102 ± 7
South	0	311 ± 56	1255 ± 34	2	18 ± 2	69 ± 6
	5	365 ± 36	1325 ± 45	7	26 ± 2	80 ± 7

Note: [a] **Nine animals in the Northeast region; 3 animals each in the other regions**
[b] **Of number of calves born**

The overall production performance during the project period of five years is presented in Figs. 10, 11 and 12.

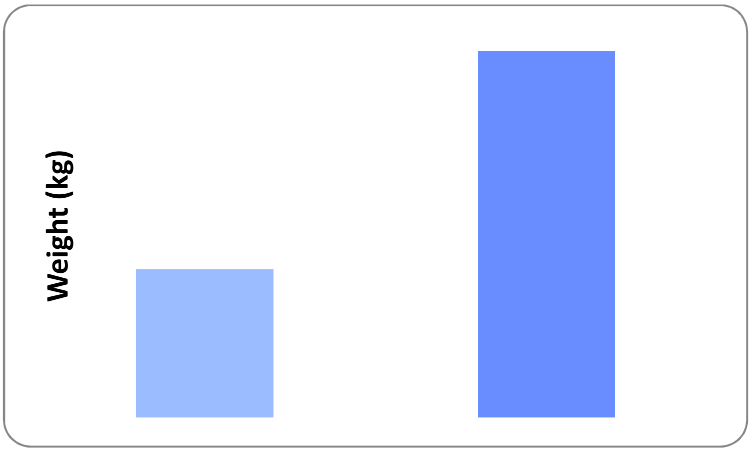

FIG. 10. Average body weight (kg)of cattle during the project period of five years.

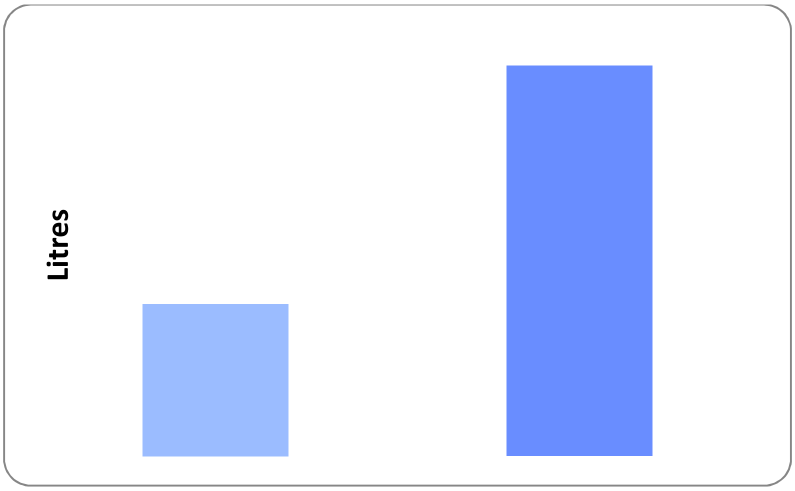

FIG. 11. Average milk yield (litres) during the project period of five years.

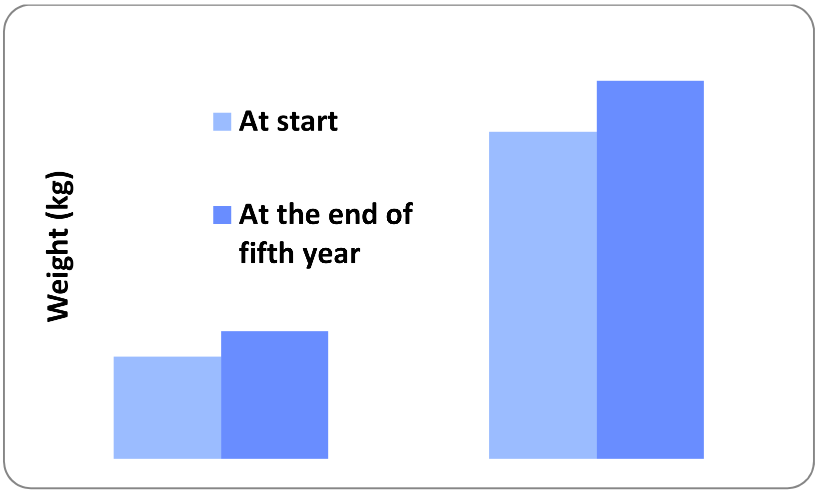

FIG. 12. Average birth weight (kg) and average weaning weight (kg) of calves during the project period of five years.

The number of calves born also increased at the end of five years of the project. Additionally, the calf average birth weight and average weaning weight significantly ($p<0.01$) increased in the fifth year from the initial year in all agro-climatic zones. The average birth weight increased due to feeding the cattle according to the nutrient requirement at various stages of pregnancy. Singh et al. [13] reported that the proper feeding of cattle with adequate energy, protein, vitamins and minerals increases the average birth weight of the calf. The average weaning weight was found to increase due to feeding the calf with calf starter feed beginning from 15 days after birth [14].

3.11. Reproduction Performance of Dairy Cattle

The reproduction performance of dairy cattle per region at the beginning and end of the 5-year experimental period is given in Table 12.

TABLE 12. REPRODUCTION PERFORMANCE (MEAN[A] ± SE) OF DAIRY CATTLE AT THE BEGINNING AND END OF THE FIVE-YEAR PERIOD IN FOUR REGIONS

	Time (yr)	Calving interval (mo)	1st insem-ination (d)	Services concept-ion^{-1}	Herd rate (%) of			Dry period (d)
					Heat detection	Conce p-tion	Preg-nancy	
North east	0	13 ± 2	93 ± 3	4.3 ± 0.7	44 ± 2	36 ± 2	16 ± 1	96 ± 10
	5	12 ± 1	79 ± 3	2.5 ± 0.2	48 ± 2	51 ± 3	25 ± 1	62 ± 6
Delta	0	15 ± 3	85 ± 5	6.3 ± 0.5	31 ± 1	32 ± 2	10 ± 1	99 ± 4
	5	13 ± 2	62 ± 2	2.9 ± 0.2	47 ± 2	54 ± 3	25 ± 1	65 ± 5
West	0	18 ± 2	86 ± 4	5.8 ± 0.3	49 ± 2	48 ± 3	23 ± 1	118 ± 17
	5	13 ± 2	76 ± 4	2.5 ± 0.5	69 ± 3	75 ± 4	52 ± 2	95 ± 6
South	0	14 ± 3	93 ± 5	5.0 ± 0.7	35 ± 2	34 ± 2	12 ± 1	114 ± 11
	5	14 ± 2	79 ± 7	2.0 ± 0.3	71 ± 3	71 ± 3	50 ± 3	75 ± 5

Note: [A] Nine animals in the North-east region; 3 animals in each of the other regions

The overall mean effects on reproduction performance are presented in Figs. 13, 14, and 15.

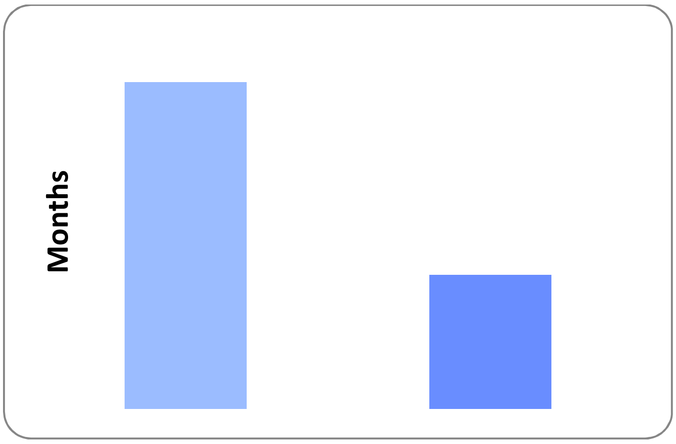

FIG. 13. Average calving intervals in months of dairy cattle during the project period of five years.

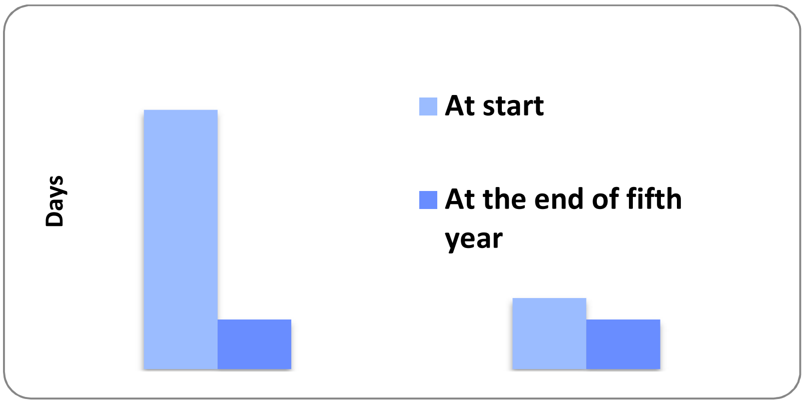

FIG. 14. Average days for 1st insemination and dry period (days) of dairy cattle during the project period of five years.

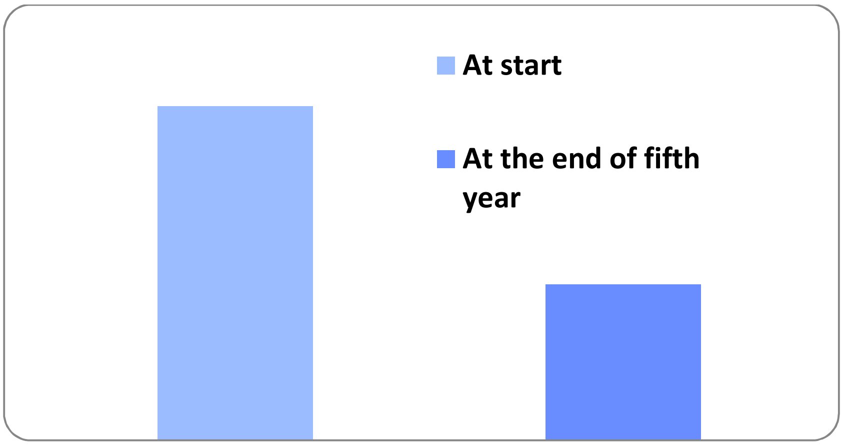

FIG. 15. Average number. of service per conception of dairy cattle during the project period of five years.

As shown in Table 12 and Figs. 13–15, the calving interval average days for the 1st insemination, number of services per conception and dry periods decreased significantly ($p<0.01$) from the first to the fifth year of the project. The cattle were maintained with sufficient supplementation of protein through leguminous fodder, and the concentrate was fed with 16% crude protein. The changes in reproductive performance could be attributed to the vitamins and other nutrients available from quality green fodder, which was available throughout the year. Ibtisham et al. [15] reported that the nutritional requirements increase rapidly with milk production after calving, but an improper diet could result in a negative energy balance (NEB). NEB delays the time of the first ovulation through uncoupled production of hormones. A diet high in fat could prevent the NEB state by increasing the energy status of animals. Protein supplementation supports high production but can also have severe effects on the reproductive performance of the animal.

Since the animals were in a good plane of nutrition, the heat detection rate, the conception rate, and the pregnancy rate of the herd also significantly ($p<0.01$) increased at the end, in comparison to the start, of the project period. Adequate nutrition before calving and during the post-partum period is essential if acceptable oestrus and rebreeding performance are to be achieved [16]. Alam and Sarder [17] also reported that proper feeding improved the reproductive and productive traits, while the pregnancy rate was significantly ($p<0.05$) affected by age, BCS, and body weight.

3.12. Production Performance of Goats

Production performance of goats during the project period of five years at all experimental agro-climatic zones are presented in Table 13.

TABLE 13. PRODUCTION PERFORMANCE (MEAN ± SE) OF GOATS AT THE BEGINNING AND END OF THE FIVE-YEAR PERIOD IN FOUR REGIONS

Region	Time (years)	Average body weight (kg)[a]	Kids born	Average[b] weight (kg)		
				Birth	Weaning	Adult[c]
North east	0	21.8 ± 2.2	4	1.7 ± 0.2	4.8 ± 0.7	20.5 ± 2.7
	5	24.4 ± 0.7	37	2.1 ± 0.1	6.5 ± 1.4	26.1 ± 2.4
Delta	0	23.6 ± 1.8	2	2.3 ± 0.2	7.3 ± 1.4	29.7 ± 2.3
	5	33.3 ± 2.8	33	2.9 ± 0.8	10.6 ± 3.2	31.6 ± 2.3
West	0	26.4 ± 2.7	2	2.2 ± 0.6	9.5 ± 2.0	28.2 ± 1.6
	5	31.8 ± 2.8	43	2.8 ± 0.8	14.3 ± 2.9	30.5 ± 4.2
South	0	20.5 ± 2.7	3	2.1 ± 0.2	3.6 ± 1.6	26.4 ± 2.6
	5	36.6 ± 3.2	19	3.0 ± 0.3	7.6 ± 0.4	28.5 ± 2.1

Note: [a] **Nine animals in the Northeast region; 3 animals in each of the other regions**
[b] **Of number of kids born**
[c] **At one year of age**

The average body weight of goats significantly ($p<0.01$) increased in the fifth year compared with the first year of the project in all experimental agro-climatic zones. The gain in weight could be attributed to the good quality of the green fodders, which were available from the integrated crop and fodder cultivation. The feeding schedule was changed every month according to the physiological stage and body weight of the goats. The animals were fed with 6% of dry matter according to their body weight. The intake of dry matter (DMI) increased linearly when goats were offered more feed. DMI of goats is influenced by several factors, namely feed quality, coarseness, palatability, roughage: concentrate ratio, animal behaviour and physiological stage [18]. Sultana et al. [19] reported that the daily supplementation of concentrate with *ad libitum* roughage increases the feed conversion efficiency and the production performance of goats. The average effect on production performance of goats during the project period of five years is presented in Figs. 16 and 17.

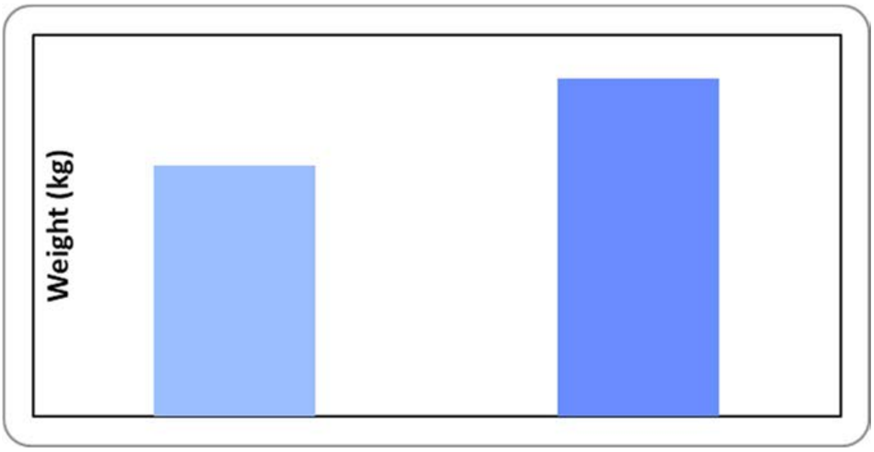

FIG. 16. Average body weight (kg) of goats during the project period of five years.

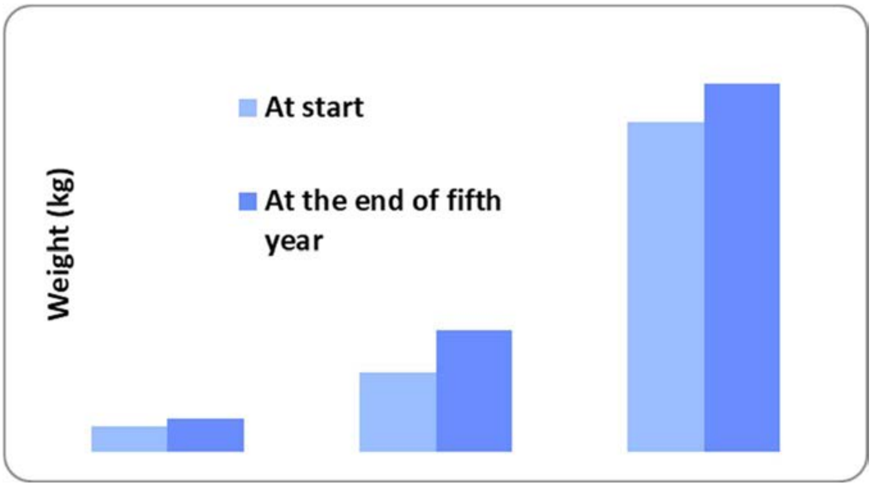

FIG. 17. Average birth weight (kg) of kids, average weaning weight (kg) of kids and average adult body weight (kg) at one year of age during the project period of five years.

The numbers of kids born also increased at the end of five years. The average birth weight and average weaning weight of kids significantly ($p<0.01$) increased in the fifth year compared with the first year of the project in all experimental agro-climatic zones. The average birth weight of kids increased due to feeding the dam according to the nutrient requirement at various stages of pregnancy. The increased birth weight of kids in turn led to an increase in the weaning weight due to the good plane of nutrition. The average weaning weight of kids also increased due to feeding with concentrate feed beginning from 15 days after birth. Gul et al. [20] found that additional feeding of kids resulted in an increased average weaning weight. The kids reach adult age at one year and the average adult weight also significantly ($p<0.01$) increased in all regions at the end of five years. The kids were well maintained with adequate protein in the diet from 15 days of age and allowed to grow with the dam to get milk until weaning age. From the time of weaning, the kids were allowed to take *ad libitum* quantity of leguminous and non-leguminous fodder with concentrate feed. The feed and fodder were increased according to the body weight of the goat. This could be attributed to the additional supplement of protein, vitamins and minerals to increase the goat adult weight.

3.13. Reproduction Performance of Goats

The indices of reproduction performance of goats in each region over five years are given in Table 14 and the overall effect on the reproduction performance is presented in Figs. 18 and 19.

TABLE 14. REPRODUCTION PERFORMANCE (MEAN[A] ± SE) OF GOATS AT THE BEGINNING AND END OF THE FIVE-YEAR PERIOD IN FOUR REGIONS

Region	Time (yr)	Average age (mo) at 1st		Average Nº FTP[a]	Proportion of live births	Interval (months)	
		Estrus	Kidding			Kidding	PPH[b] period
North east	0	12.0 ± 1.7	17.5 ± 2.6	0.75 ± 0.04	0.83 ± 0.05	9.4 ± 0.9	3.54 ± 0.97
	5	8.6 ± 1.5	13.7 ± 1.9	1.00 ± 0.06	1.00 ± 0.05	7.3 ± 0.4	2.01 ± 0.04
Delta	0	11.1 ± 2.5	17.3 ± 1.6	0.64 ± 0.03	0.75 ± 0.03	12.1 ± 1.0	3.16 ± 0.87
	5	10.2 ± 1.7	14.6 ± 1.9	0.98 ± 0.04	1.02 ± 0.05	8.3 ± 1.8	2.48 ± 0.42
West	0	11.1 ± 1.5	15.1 ± 2.6	0.82 ± 0.03	1.00 ± 0.03	11.1 ± 2.5	3.54 ± 0.71
	5	9.1 ± 2.3	13.8 ± 1.9	1.05 ± 0.05	1.01 ± 0.02	8.7 ± 1.7	2.53 ± 0.82
South	0	11.6 ± 2.5	18.6 ± 3.6	0.89 ± 0.04	0.76 ± 0.03	12.1 ± 2.5	4.09 ± 0.61
	5	10.5 ± 0.8	13.6 ± 1.6	1.00 ± 0.06	1.00 ± 0.04	11.0 ± 2.4	2.15 ± 0.54

Note: **[A] Nine animals in the Northeast region; 3 animals in each of the other regions**
[a] FTP, full term parturition
[b] PPH, post-partum heat

The age at first estrus and average age at first kidding decreased significantly ($p<0.01$) from start of the project to the end of the project in five years. Similarly, the kidding interval and post-partum heat period also decreased significantly ($p<0.01$) during this period. The goat was maintained with good protein supplementation through the feeding of leguminous fodder and concentrate with 16% crude protein. The changes in reproductive performance could be attributed to the vitamins and other nutrients available from quality green fodder, which was available throughout the year. The average numbers of full term parturition and kids born increased significantly ($p<0.01$) from first to the fifth year. Sultana et al. [20] reported that concentrate supplementation increased the feed intake of does, the age at first estrum, and the age at first kidding, but the positive effect was correlated with the level of supplementation. Daily supplementation of 250 g of concentrate to goats in addition to *ad libitum* roughage feeding could support the full term parturition and live kids born. The reproduction performance is improved under a well maintained feeding regimen with good quality non leguminous and leguminous fodders. The availability of fodder is maintained throughout the year by recycling the nutrients in excreta in integrated farming. Ben Salem [21] found that the reproduction performance of goats was improved with nutritionally balanced feed through concentrate and fodders. He also suggested that it could be possible to maintain the availability of quality fodder throughout the year.

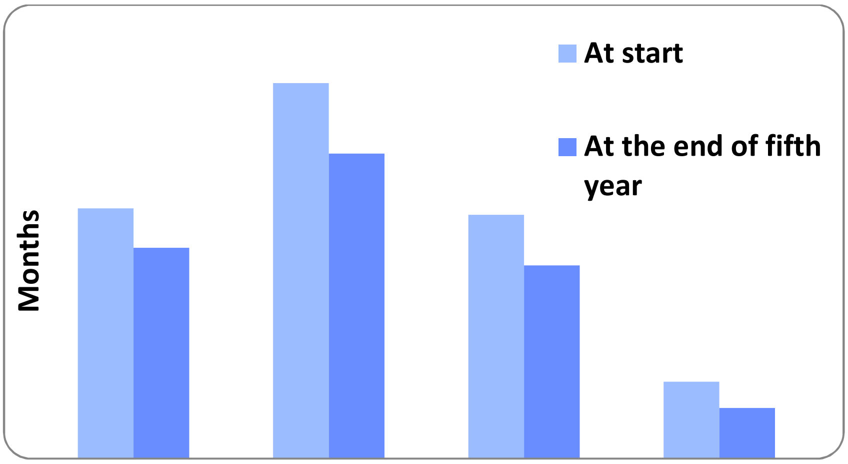

FIG. 18. Average age at first estrus, average age at first kidding, kidding interval and post-partum heat period during the project period of five years.

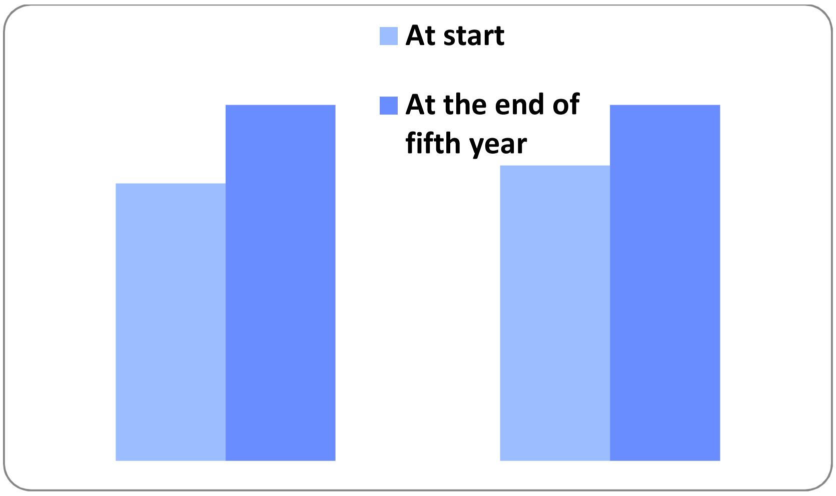

FIG. 19. Average number of full-term parturition and average number of kids born (live/total) during the project period of five years.

4. CONCLUSIONS

Soil nutrients including nitrogen and organic carbon were recycled through crop residues, fodder, and animal excreta through integrated cropping-livestock systems.

- Mean soil nitrogen and organic carbon levels were maintained during the project period of five years by recycling dung and urine.
- Irrigation water consumption for every kg of crop and green fodder produced decreased when the SRI cultivation and drip irrigation was introduced in green fodder cultivation.
- Paddy, paddy straw, and biomass yield of green fodder increased during the project period of five years in all regions through utilization of farmyard manure.

- Water conservation reached 37.5% in the paddy fields of all experimental zones and water was conserved by 24% in *Desmanthus virgatus* fields of the north eastern and delta zones until the fifth year.
- During the five years, the calf birth weight and weaning weight increased by 20.5% and 10.5%, respectively. The dairy cattle weight was maintained according to the physiological status. Overall milk yield also improved in five years.
- The reproduction performance of dairy cattle increased by reducing the average time for the first insemination from 107.5 to 75 days in all experimental zones.
- During five years, the goat kid birth weight, kid weaning weight and adult weight also increased by 23.97%, 10.25% and 19%, respectively.
- The reproduction performance of the goat also increased as evidenced by a reduced kidding interval, reduced age at first estrus and age at first kidding from 10.6 to 7.3 months, 11.3 to 10.8 months and 15.8 to 14.9 months, respectively.

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ENHANCING SOIL PRODUCTIVITY AND WATER AND NUTRIENT USE EFFICIENCIES IN INTEGRATED CROPPING-LIVESTOCK PRODUCTION SYSTEMS IN KENYA

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Abstract

The arid and semi-arid lands (ASALs) of Kenya cover over 83% of the total land mass and are dominated by smallholder farmers most of whom practice mixed farming with varying degrees of crop–livestock integration. Despite the increasing demand for crop and livestock products from an increasing ASAL population, yields are decreasing as a result of low and declining soil fertility and adverse climate variability, which is increasingly becoming unpredictable due to impacts of climate change. A field experiment was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Katumani research farm from 2013 to 2018 to address these constraints. The objective was to develop and disseminate technologies that increase efficiency of water and nutrient use in rain fed smallholder crop-livestock production systems for improved productivity per unit area and enhanced household food and income security under changing climate conditions. Two tillage systems, flat conventional and tied ridges were tested for water conservation, in combination with sole or intercropped cropping systems and three soil fertility management practices (5 t farm yard manure (FYM) ha-1, 2.5 t FYM microdosed with 20 kg N and 20 kg P2O5 inorganic fertiliser ha-1 and no fertiliser application). Maize (Zea mays), cowpea (Vigna unguiculata), and lablab (Dolichos lablab) were used as test crops in a split-split plot design. Soil moisture content was observed at various soil depths and dates using a neutron probe. Grain and aboveground biomass yields from each plot were weighed at the end of every season and results adjusted and used to compute yields per hectare. Soil and crop data were subjected to analysis of variance (ANOVA) and differences in means determined at $P \leq 0.05$. The tied-ridge system had higher soil moisture with time but with no significant effect on crop yields. Significantly higher grain yields were obtained from sole crops whereas higher total biomass yields were obtained from intercropped systems. Combinations of FYM and inorganic fertiliser significantly increased grain and biomass yields. For enhanced productivity in maize based integrated cropping-livestock farming systems in the ASALs there is a need for promotion of microdosing of 2.5 t FYM with 20 kg N and 20 kg P2O5 inorganic fertilisers ha-1 for increased crop production and incorporation of cereal/legume intercrops for higher biomass yields to be used as livestock feed.

1. INTRODUCTION

Agricultural systems in arid and semi-arid lands (ASALs) of sub-Saharan Africa (SSA) are dominated by mixed farming involving varying degrees of crop-livestock integration [1]. This integration of crops with livestock in agricultural production systems is a win-win strategy, which provides a variety of economic and ecological benefits. As a risk coping strategy, livestock in mixed farming systems provide an important avenue for farm nutrient cycling. Animals provide manure to sustain crop yields, while crop residues and forage provide feed for livestock. The use of animal power on-farm alleviates labour shortages and improves the quality and timeliness of farming operations thereby increasing farm productivity and the efficiency of product value chains in mixed farming systems [2]. Ecological benefits of integrated cropping-livestock systems include conservation of natural resources through reduced usage of inorganic fertilisers, enhancing ecosystem services and environmental sustainability, providing natural pest control, improving soil quality and consequently crop yields.

The majority of the mixed farming systems in the ASALs of SSA are smallholder systems, which rely mainly on rain fed conditions and have livestock as an important multipurpose component of the farming systems [3 and 5]. Their productivity is greatly affected by the high variability in rainfall amounts and distribution as well as the inherent problem of low soil fertility. Generally agricultural productivity in the ASALs is low with further decline likely to occur as a result of increased frequencies of droughts and floods as well as increases in temperatures and loss of soil moisture associated with the impacts of climate change [6]. Despite this low productivity, the human population in the ASALs is increasing with a resultant increase in demand for crop and livestock products.

Changes in population and climatic conditions in the ASALs and the associated economic, social, and institutional changes (including increased demand for land for agricultural production and settlement) have created the need to transform crop and livestock production systems from those based on extensive grazing to ones that are more intensively managed. As concern about poverty, food security, and environmental degradation in sub-Saharan Africa increases due to climate change impacts, it is important that these systems are transformed and intensified along productive and sustainable pathways. This needs to be done in line with current agricultural commercialization policies that focus on the agricultural product value chains. Introduction, adaptation, and implementation of good farming practices in these mixed farming systems are therefore needed to address the challenges of increasing global population, food scarcity, and building agricultures resilience to climate change. Such good farming practices are also important in order to maintain local and national food security and livelihoods, improve agricultural resource use efficiency, and provide social and economic benefits. Persuading farmers to adopt integrated cropping-livestock production systems (ICLS), and policy makers to provide institutional support for implementing these systems, is critically important. Success depends on the provision of quantitative information on the economic, environment and resource use benefits of such systems.

In view of the above factors, new and sustainable climate-smart agricultural systems that not only support increased food and fodder production but also conserve the natural resource base need to be explored; otherwise resource-poor farmers who depend directly on these production systems may be adversely affected by the changing climate variability. Lower eastern Kenya is one such semi-arid region with a mixed crop-livestock system. Maize, cowpea and dolichos are some of the crops grown in the area. Maize is the most common staple food crop in the area and farmers also use the maize seed and stover as feed/fodder or for fuel. Cowpea is used in the preparation of several dishes. The crop is good for nitrogen fixation and soil improvement while leftovers after removal of grain are fed to livestock. Sometimes the grain is fed to livestock especially poultry. Dolichos, on the other hand, is a legume whose iron rich seed is used for human consumption. The crop is an excellent fodder and soil cover crop. Most of the livestock in lower eastern Kenya are kept under free range systems with low management and productivity. Unavailability of water and feed as a result of low and poorly distributed rainfall is common especially during the dry periods.

Soil water conservation through tillage is widely accepted as one of the ways of improving agricultural productivity in rain fed agriculture [7 and 9]. Conservation tillage, mulching, tied ridging, ripping, and deep tillage have been suggested as the possible methods of rainwater conservation which are also likely to improve agricultural productivity where water is scarce for irrigation or farmers do not have resources for irrigation [9 and 11]. Some of the justifications associated with tied ridging include its potential to enhance water infiltration, increase soil water retention and improve crop yields. The efficiency of soil water conservation measures is enhanced when used in combination with other soil management practices such as proper cropping systems. Introduction of crops and farming practices that incorporate both human and animal feeds and improve soil conditions is therefore, necessary for enhancing food production and improving the natural resource base.

This study was carried out by the Kenya agricultural and Livestock Research Organization (KALRO) in collaboration with the Ministry of Agriculture and Livestock and Fisheries (MoL&F) and the International Atomic Energy Agency (IAEA) to optimize soil and water use efficiency to enhance both crop and livestock productivity in in the dry lands of Eastern Kenya. The overall objective was to enhance food security and rural livelihoods by improving resource use efficiency and sustainability of ICLS under a changing climate. The specific objectives were to i) assess socio-economic and environmental benefits of crop-livestock systems, ii) develop soil, water and nutrient management options in integrated cropping-livestock systems for potential adoption by farmers in Kenya, iii) assess the influence of ICLS on GHG emissions, soil carbon sequestration and water quality, and iv) strengthen the capacity of scientists and other stakeholders. The project entailed conducting socio-economic surveys, field trials and on-farm demonstrations in two watersheds. This paper focuses on the development of best-bet soil, water and nutrient management options for use in ICLS in Kenya.

2. METHODOLOGY

2.1. Study Site

Field trials were conducted from 2013 to 2017 at the Kenya Agricultural and Livestock Research Organization-Agricultural Mechanization Research Institute Katumani farm (01º 35'S 37º 14'E) in Machakos County in semi-arid eastern Kenya. The site lies at an altitude of 1575 m above sea level (a.s.l) in agro-climatic zone IV. According to Jaetzold et al. [12] the area exhibits low and variable rainfall with a bimodal pattern. The rainfall seasons, which are also the cropping seasons, occur in March-May (MAM) and October-December (OND) and are referred to as the long rain (LR) and short rain (SR) seasons, respectively [12]. The SR season is more reliable in rainfall amounts and distribution than the LR. The average annual rainfall is 656 mm per annum (p.a.) with seasonal averages of 272 mm in LR and 382 mm during the SR season [13]. The two rainy seasons are separated by an extended dry period, which lasts from mid-July until mid-October. This period is characterized by low availability of livestock feed.

Mean maximum and minimum annual temperatures are 24.7°C and 13.7°C, respectively (Fig. 1). Rates of evapotranspiration are high and exceed precipitation for most parts of the year [12]. Soils are classified as Chromic Luvisols [14]. These are low in inherent soil fertility (5–10 g kg^{-1}carbon and 0.7–0.9 g kg^{-1} nitrogen) with a slightly acidic reaction (pH 5.7–6.9 in water). The surrounding area is occupied by farmers, mainly smallholders, practicing integrated cropping-livestock farming (ICLF) on an average of 2.5 hectares of land.

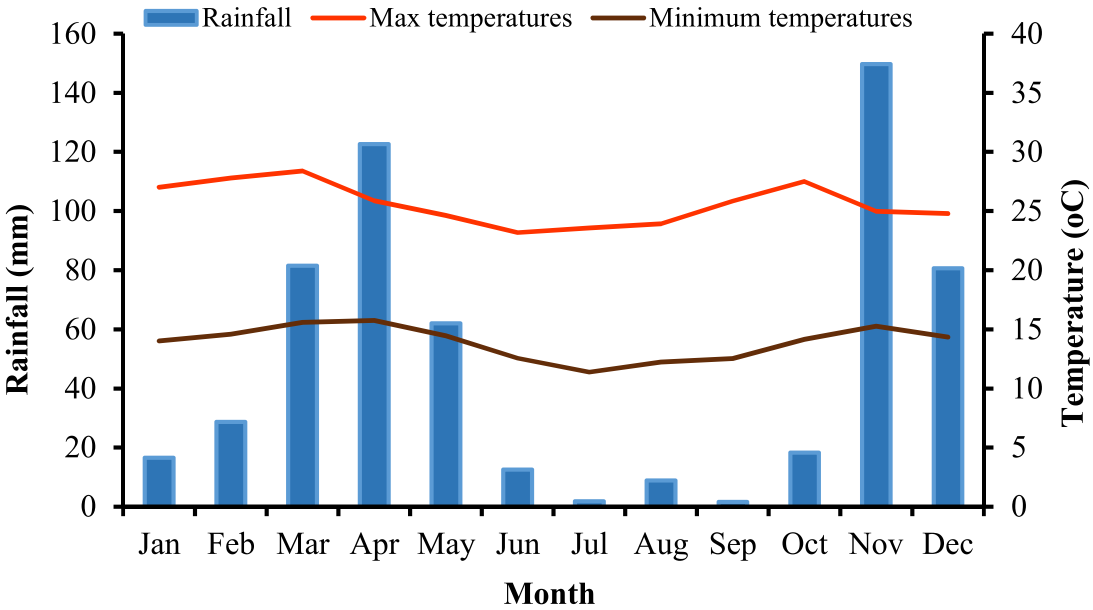

FIG. 1. Average rainfall and temperatures during the study period (2013-2017) at KALRO Katumani Agricultural Machinery Research Institute.

2.2. Experimental Design And Treatments

A split-split plot design was used with individual treatments arranged in a Randomized Complete Block Design (RCBD) replicated four times. Treatments consisted of combinations of two tillage systems, five cropping systems and three fertiliser management practices. Tillage systems were allocated to the main plots, cropping systems to the sub-plots and fertiliser management to the sub-sub plots. Individual sub-sub plots were 5 × 5 m in dimension.

2.3. Tillage Systems

Tillage practices tested for adoption were tied ridges and the flat (conventional method) as the control. Tied ridges are discontinuous furrows made by crossties that interrupt water flow in the furrow thereby creating pools that retain water for a while and promote slow seepage [15]. The tied ridges form closely spaced rectangular depressions, which prevent redistribution of water within the field and concentrates it in the furrow bottom near the root zone. In this trial ridges were made using the ordinary hand hoe at 0.9 m or 1 m inter-row spacing depending on the crop to be planted in the specific plots. The ridges were tied at 2 m intervals. They were maintained throughout the trial period by reconstructing them just before planting and during weeding. This system was compared to the flat tillage system where no ridges are left in the field, and which is also the conventional method used by farmers in the area.

2.4. Cropping Systems

Drought tolerant crop varieties consisting of one cereal food crop, legume food crop, and forage legume were tested. These were maize (*Zea mays*), cowpea (*Vigna unguiculata)* and lablab (*Dolichus lablab*), respectively. The test crops were selected based on their dual utilization as human food and livestock feed. The crops were planted in five crop combinations (1) sole maize, (2) sole cowpea, (3) sole lablab (4) maize/cowpea intercrop and (5) maize /lablab intercrop. Dry land maize variety Katumani composite 1 (KCB1), cowpea variety K80 and, Dolichos lablab (brown) were used. In the sole crop plots maize was planted at 0.9 m between rows and 0.3 m within rows (hill spacing), cowpea at 0.6 m between rows and 0.25 m within rows, and Dolichos at 1 m between rows and 0.5 m within rows. In intercrop systems single rows of cowpea or Dolichos were planted between maize rows. The legume hill spacing in intercrops were 0.25 m for cowpea and 0.5 m for Dolichos.

2.5. Fertility Treatments

Soil fertility treatments were zero (0 kg fertiliser) as the control, 5 t FYM ha^{-1} and (3) a combination of 2.5 t FYM, 20 kg N and 20 kg P_2O_5 ha^{-1}. FYM applied consisted of a mixture of cow and goat manure. The N and P_2O_5 were applied as calcium ammonium nitrate (CAN) and triple supper phosphate (TSP), respectively. The above practices were combined into 30 treatments as summarized in Table 1.

2.6. Data Collection and Statistical Analysis

Soil moisture data were collected using the neutron probe at different periods of the growth of the crop. Data for determination of final crop biomass and grain yield were collected from plants harvested from the net area after discarding the border rows and the end plants of each centre row. Maize ears were separated from the stover and legume pods from the straw and their fresh weight determined. A subsample of each plant component was oven dried at 70ºC for 48 hours and dry weights determined. Dry grain and stover/straw yields were then calculated from the fresh weight and moisture content for extrapolation of weights per hectare. Grain weight was calculated at 12–13% moisture content. Rainfall data for the period of the experiment was sourced from the meteorological station located within the institute.

Analysis of variance was performed on all measured variables using Proc ANOVA Model in GenStat, 2007 statistical Software. In the split-split-plot model, tillage was used as the main plot, cropping systems as sub-plots and fertility as the sub-sub plots. Effects of cropping system were assessed by comparing yields of individual crops in sole and intercropped systems in the analysis. The effect of fertility was assessed by comparing yields of individual crops in sole or intercropped systems under different fertility treatments. Means of significantly different treatments were separated using the Fisher's Protected LSD ($P \leq 0.05$) test. Rainfall data were consolidated and the distribution was represented graphically.

TABLE 1. SUMMARY OF TREATMENTS FOR ON-STATION EXPERIMENT

Treatment	Tillage practice	Cropping system	Fertiliser application (ha^{-1})
T_1	Tied ridges	Sole maize	0 kg
T_2			5 t ha^{-1} FYM
T_3			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_4		Sole cowpea	Zero fertiliser
T_5			5 t ha^{-1} FYM
T_6			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_7		Sole lablab	Zero fertiliser
T_8			5 t ha^{-1} FYM
T_9			2.5 t FYM + 20 kg N + 20kg P_2O_5
T_{10}		Maize/cowpea intercrop	Zero fertiliser
T_{11}			5 t ha^{-1} FYM
T_{12}			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_{13}		Maize/lablab intercrop	Zero fertiliser
T_{14}			5 t ha^{-1} FYM
T_{15}			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_{16}	Flat	Sole maize	Zero fertiliser
T_{17}			5 t ha^{-1} FYM
T_{18}			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_{19}		Sole cowpea	Zero fertiliser
T_{20}			5 t ha^{-1} FYM
T_{21}			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_{22}		Sole lablab	Zero fertiliser
T_{23}			5 t ha^{-1} FYM
T_{24}			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_{25}		Maize/cowpea intercrop	zero fertiliser
T_{26}			5 t ha^{-1} FYM
T_{27}			2.5 t FYM + 20 kg N + 20 kg P_2O_5
T_{28}		Maize/lablab intercrop	zero fertiliser
T_{29}			5 t ha^{-1} FYM
T_{30}			2.5 t FYM + 20 kg N + 20 kg P_2O_5

3. RESULTS AND DISCUSSION

3.1. Water

3.1.1. Rainfall distribution

Rainfall amounts at the experimental site varied during the period of study (2013–2017) across and within the seasons. The rainfall distribution during 2013, 2014, 2015 SR and 2014, 2015 LR seasons is shown in Fig. 2. Rainfall distribution in the two years presented below was generally poorer during LR than in SR seasons with amounts and number of rainy days reducing greatly at the flowering and grain filling period (month of May). Such poor distribution and dry spells especially at the grain filling stage have been reported to have negative effect on crops yields [16, 17].

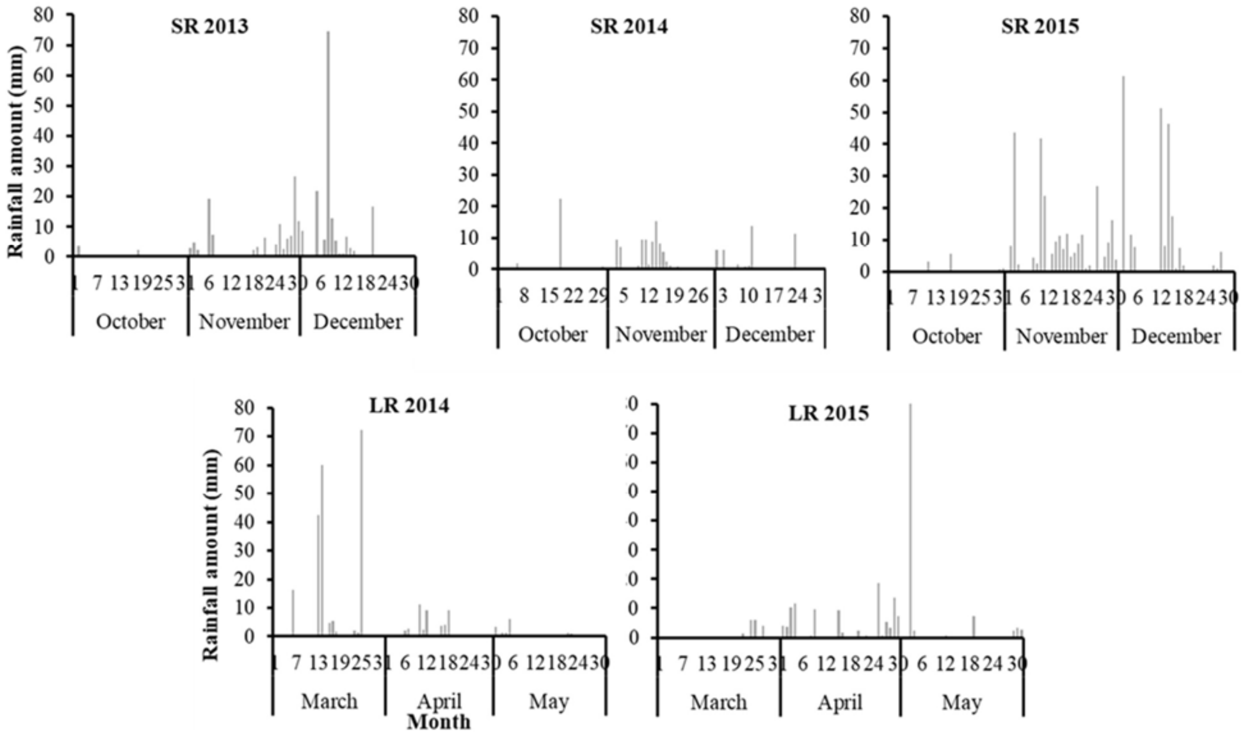

FIG. 2. Rainfall distribution during SR and LR seasons from 2013-2015.

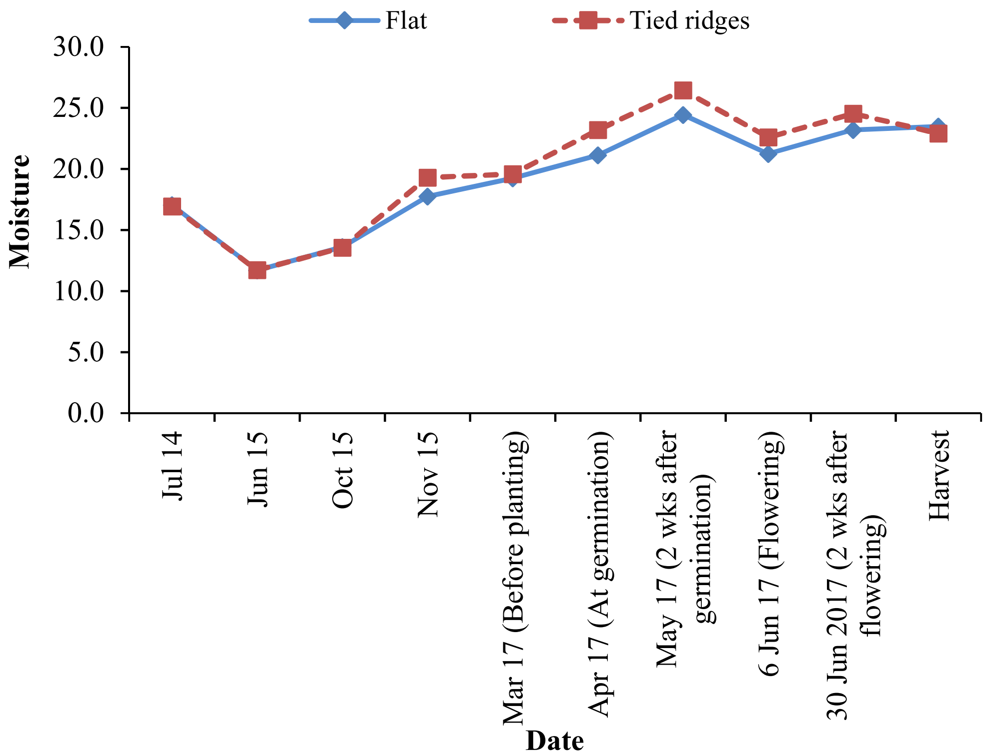

FIG. 3. Soil moisture content in flat and tied ridge systems at different sampling dates.

3.1.2. Tillage systems and soil moisture content

There was a significant interaction of tillage with the time of moisture sampling ($P<0.001$). An increase in soil moisture content with time was realized in both systems. Tied ridge tillage had higher soil moisture compared to conventional flat tillage at different sampling periods as depicted in Fig. 4. However, when averaged across years and cropping systems, tied ridging did not have a significant effect on crop grain or biomass yields. These findings are in agreement with reports by Karuma et al. [9] and Miriрti et al. [18] in their studies in the dry lands of Eastern Kenya, where they found increases in soil moisture contents under different tillage systems including tied ridges. Motsi et al. found similar results [19]. However, in contrast, Gürsoy et al. [20] in studies in semi-arid Turkey reported reduced moisture in ridge tillage. This may imply that the effect of tied ridges on soil moisture depends on other localized factors.

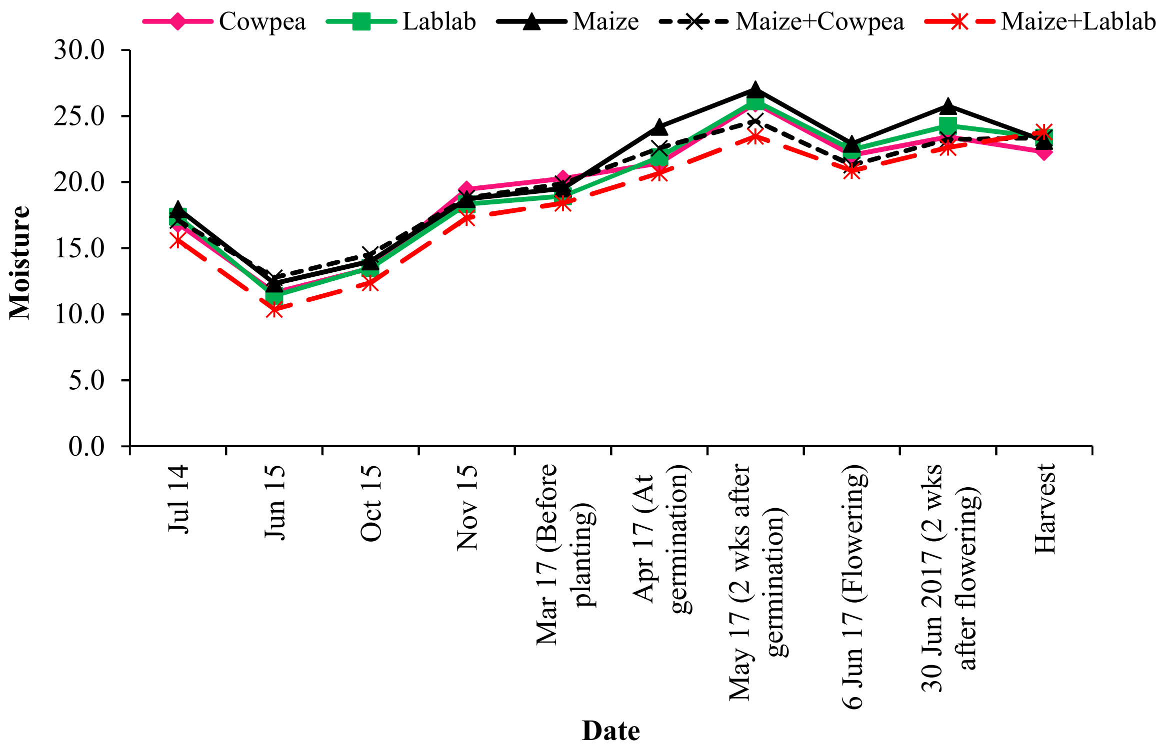

FIG. 4. Soil moisture content under different cropping systems and sampling dates.

3.1.3. Soil moisture content in different cropping systems

There was significant interaction of the different cropping systems with time on soil moisture content (Fig. 5). Generally, soil moisture in all the cropping systems varied at different sampling stages but increased significantly with time from the beginning of the study. This may have been due to differences in the rainfall received. Higher soil moisture was also recorded in sole crop plots compared to those with intercrops. The highest moisture content was recorded in May 2017, two weeks after germination of the 2017 SR season crop. During this sampling event plots with sole maize system had significantly higher moisture content (27.0 cm^3 cm^{-3}) than those with the maize/lablab intercrop system (23.5 cm^3 cm^{-3}) (LSD = 1.75). Higher moisture content in sole crops compared to intercrops may probably have been due to competition for moisture in these low rainfall areas.

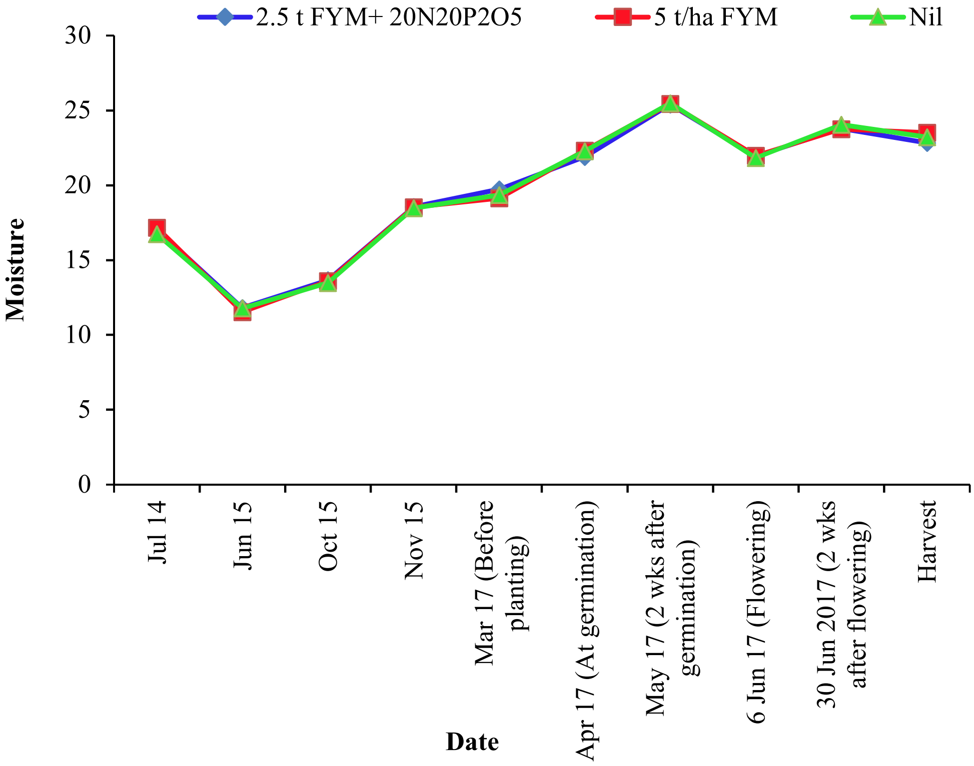

FIG. 5. Effect of fertility on soil moisture content.

3.1.4. Soil moisture and fertility management practices

There was no significant effect of different fertiliser management practices on soil moisture content. However, a significant interaction was found between fertility and time of sampling where soil moisture was found to increase in different treatments with time (Fig. 6).

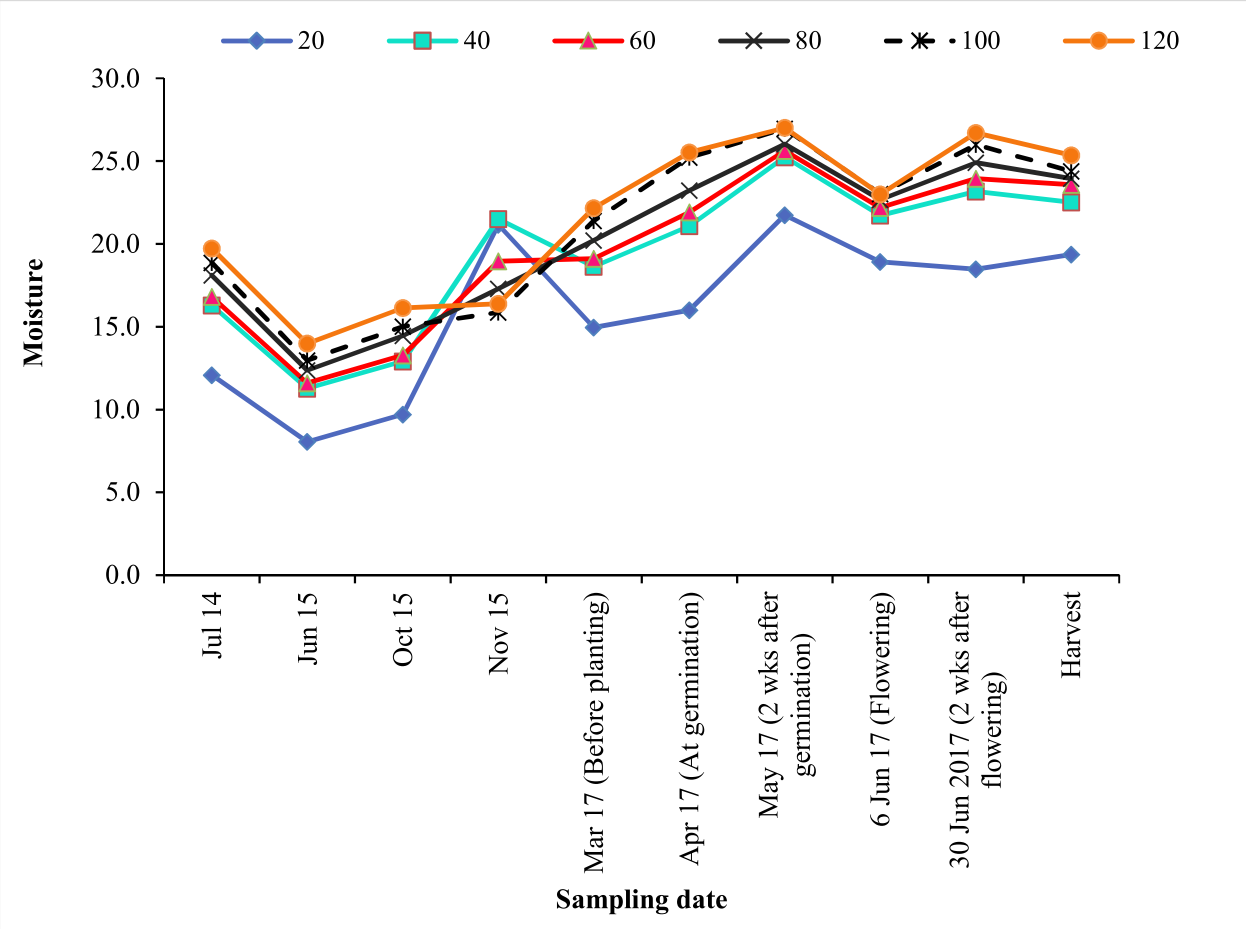

FIG.6. Soil moisture content at different soil depths and dates of sampling.

3.1.5. Soil depth and soil moisture content

A significant interaction effect on soil moisture content was found at the different soil depths with time. A general increase in soil moisture content with depth in the soil profile (Fig. 7) was noticed where the upper profile (0–20 cm) which hosts most of the crop roots had the least moisture during most of the sampling periods except in November 2015 when rainfall was fairly well distributed over the crop growing season. Low soil moisture in the upper profile may have been caused by evaporation losses and uptake by plant roots, thus bringing about the need for proper cropping systems and cropping patterns that reduce competitions in dry lands and protect the soil from moisture loss. The lowest depth interval (200–120 cm) on the other hand had the highest average soil moisture, which could be attributed to deep percolation of rainwater.

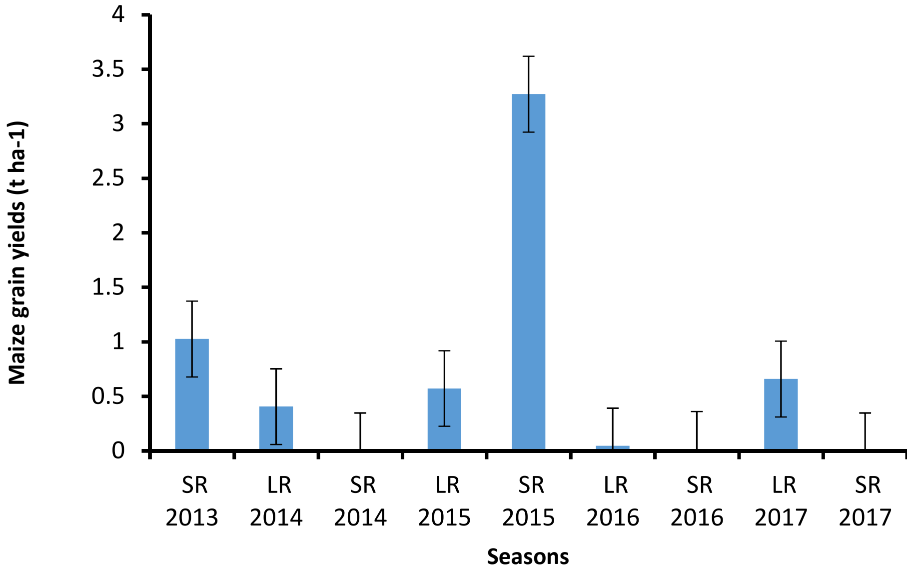

FIG. 7. Seasonal variations in maize grain yields (2013–2017).

3.2. Maize

3.2.1. Maize grain yields

The yields of maize grain under different tillage, cropping systems, and fertiliser application during SR and LR seasons over the study period are shown in Table 2. Maize yields were generally low compared to the potential yields of 2.7 t ha^{-1} stipulated by the Kenya Agricultural and Livestock Research institute [21]. The yields varied with rainfall distribution (Fig. 2). There were highly significant differences ($P < 0.001$) in yields among seasons, cropping systems and fertility. The seasonal variations in yields are shown in Fig. 8 while the effects of tillage, cropping systems and fertility on yields of maize are given in Table 3.

TABLE 2. MAIZE GRAIN YIELDS (T HA^{-1}) DURING LR AND SR SEASONS FROM THE YEARS 2013 TO 2017

Tillage	Cropping system	Fertility ha^{-1}	SR seasons					LR seasons			
			2013	14	15	16	17	2014	15	16	17
Flat	Maize/cowpea intercrop	Control	0.33	0	2.66	0.01	0	0.06	0.23	0	0.43
		FYM+N+P	0.75	0	4.75	0.01	0	0.12	0.37	0	0.36
		FYM	0.27	0	3.65	0.03	0	0.23	0.33	0	0.47
	Maize/lablab intercrop	Control	1.22	0	2.44	0	0	0.40	0.25	0	0.47
		FYM+N+P	1.18	0	4.08	0	0	1.24	0.74	0	0.70
		FYM	1.21	0	2.55	0	0	0.35	0.66	0	0.68
	Sole maize	Control	2.12	0	2.74	0	0	0.86	0.82	0	0.52
		FYM+N+P	2.16	0	6.20	0	0	1.24	1.09	0	1.30
		FYM	2.15	0	4.32	0	0	0.88	1.13	0	1.23
Tied ridges	Maize/cowpea intercrop	Control	0.06	0	2.50	0.08	0	0	0.18	0.36	0.39
		FYM+N+P	0.30	0	3.52	0.03	0	0.06	0.40	0.27	0.58
		FYM	0.16	0	1.76	0.08	0	0.01	0.28	0.16	0.38
	Maize/lablab intercrop	Control	0.49	0.49	1.68	0	0.49	0.10	0.34	0	0.49
		FYM+N+P	0.54	0	3.82	0	0	0.15	0.48	0	0.67
		FYM	0.96	0	1.77	0	0	0.15	0.45	0	0.68
	Sole maize	Control	1.65	0	3.13	0	0	0.48	0.76	0	0.51
		FYM+N+P	1.59	0	4.88	0	0	0.62	0.95	0	1.23
		FYM	1.33	0	2.42	0	0	0.33	0.82	0	0.76

TABLE 3. MAIZE GRAIN YIELDS (T HA^{-1}) OVER FOUR YEARS AVERAGED ACROSS TREATMENTS AND SEASONS

Main effect	Treatment	Season	
		SR	LR
Tillage	Flat	0.996	0.477
	Tied ridges	0.728	0.363
	P value	0.093	0.52
	LSD	0.35	0.501
Cropping system	Maize / cowpea intercrop	0.699	0.236
	Maize / lablab intercrop	0.731	0.376
	Sole maize	1.156	0.647
	P value	< 0.001	< 0.001
	LSD	0.193	0.144
Fertility	Control	0.704	0.319
	FYM + N + P	1.127	0.524
	FYM	0.755	0.417
	P value	< 0.001	< 0.001
	LSD	0.152	0.097

3.2.2. *Variation in maize grain yields with seasons*

Maize grain yields varied significantly at $P \leq 0.05$ over the LR and SR seasons during the whole period of study. Generally average yields across the seasons were higher in the SR (0.86 t ha^{-1}) than LR (0.42 t ha^{-1}). The highest yields (3.27 t ha^{-1}) were harvested in SR 2015. In the LR season the highest average yield realized was 0.66 t ha^{-1} in 2017. Comparatively higher yields in SR seasons confirm earlier reports of reliability of rains as compared to the LRs [12, 13].

Variations in seasonal grain yields could be attributed to variations in the seasonal rainfall amounts and poor distribution especially at flowering and grain filling periods. For instance, although higher yields were realized in SR seasons, no maize grain was harvested during SR 2014 and 2017. Barron et al. [22] noted that short periods of water stress during critical water sensitive development stages of crop could significantly effect on crop growth and yields. Such effect of rainfall on grain yields in the ASALs has also been reported previously [16, 18].

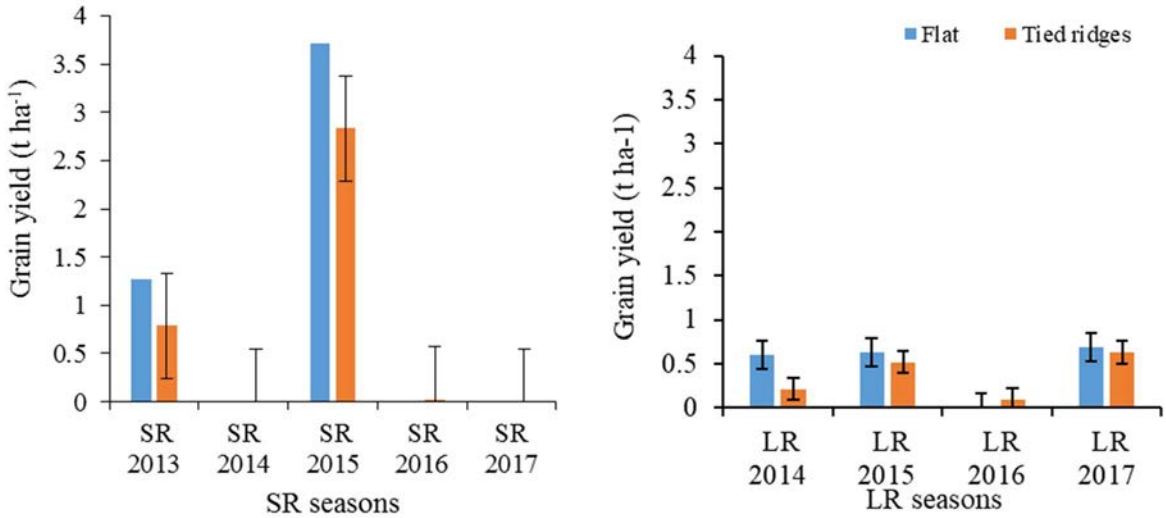

FIG. 8. Average maize grain yields in in conventional and tied ridge tillage systems during SR and LR seasons.

3.2.3. *Tillage systems and maize grain yield*

Although the main effect of tillage on grain yield was not significant, average yields from the conventional system were higher than those from the tied ridges during both seasons (Fig. 9). This was in contrast to reports from studies conducted by Karuma et al. [9] and Miriti et al. [18] who both reported increased yields from plots with tied ridges as compared to other tillage systems (mainly sub-soiling and oxen or disc ploughing).

A highly significant difference was, however, found in interactions of tillage with season. Generally maize on tied ridges yielded significantly lower than those under conventional tillage when compared across the seasons. This was in contrast to findings by Miriti et al. [18] who reported increased yields in tied ridges. Low yields in tied ridges could have resulted from the frequent destruction of ridges by heavy downpours, which may have caused some loss of nutrients compared to flat tillage (Fig. 9). This is partially supported by the fact that flat tillage yielded higher in the tillage and fertility interactions. The effectiveness of tied ridges has also been reported to depend on other factors such as rainfall received and climatic conditions within a season [9]. Crops in tied ridges are planted at the side of the ridge and their roots may not access water effectively especially during dry spells when soil moisture is lost through increased evaporation and deep percolation.

FIG. 9. Tied ridges after a heavy downpour at Katumani Research Institute.

3.2.4. Maize yields in different cropping systems

Significant differences ($P < 0.001$) in grain yields were found between effects of different cropping systems and interactions of cropping systems with seasons (Fig. 10). When averaged across all seasons, the highest maize yield (0.93 t ha^{-1}) was harvested from plots with sole maize. This was followed by 0.57 t ha^{-1} from the maize-lablab intercrop and 0.49 t ha^{-1} from maize-cowpea plots (LSD = 0.14). Averages across SR and LR seasons gave similar trends. During the SR average grain yields realized were 1.56, 0.73 and 0.7 t ha^{-1} from sole maize, maize-lablab, and maize-cowpea systems, respectively (LSD = 0.19). Average yields during LR seasons were 0.63 t ha^{-1} from sole maize, 0.38 t from maize-lablab, and 0.0.24 t ha^{-1} from the maize-cowpea system (LSD = 0.14). These results indicate that lower maize grain yield was obtained when maize was planted with cowpea than lablab. This could be because lablab established slower than cowpea thus giving less competition to maize in the early stages of establishment and growth.

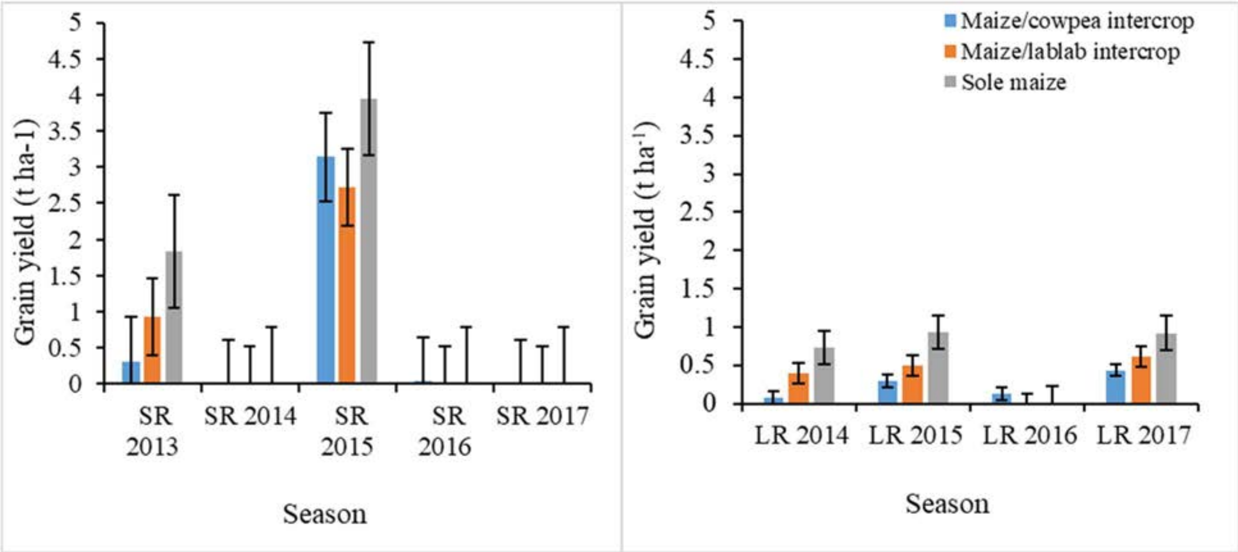

FIG. 10. Maize grain yield as affected by interactions of cropping system by season.

3.2.5. Maize yields in under different fertility practices

Different fertility treatments and interactions in fertility with seasons also had significant effects on maize grain yields during both LR and SR (Fig. 11).

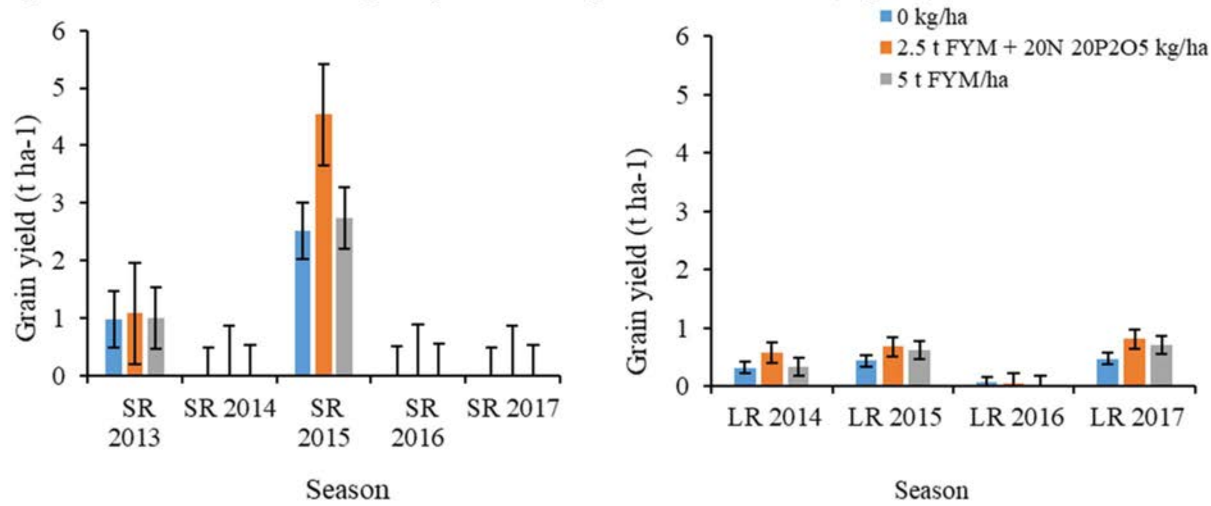

FIG. 11. Maize yields as affected by interactions of fertility and seasons.

Grain yields varied significantly with different fertiliser application practices. Yields from plots with combined application of FYM and inorganic fertiliser at the rates of 2.5 t FYM + 20 N + 20 P_2O_5 kg ha^{-1} were significantly higher (0.86 t ha^{-1}) than those from plots with 5 t FYM (0.61 t ha^{-1}) and from treatments with no fertiliser application (0.53 t ha^{-1}) (LSD = 0.09). Higher yields from plots with combined FYM and inorganic fertiliser could have resulted from enhanced crop nutrient and water use efficiencies. Farmyard manure supplied nutrients to the plant, while at the same time improved soil physical conditions, whereas inorganic fertiliser provided readily available nutrients for crop uptake, thereby enhancing availability of nutrients and water and their crop use efficiencies. Similar increases in maize yields from the supply of inorganic and organic fertilisers have also been reported in western Kenya [23] and India [24].

The effect of interactions of tillage, cropping system, and fertility during the SR season is shown in Fig. 12.

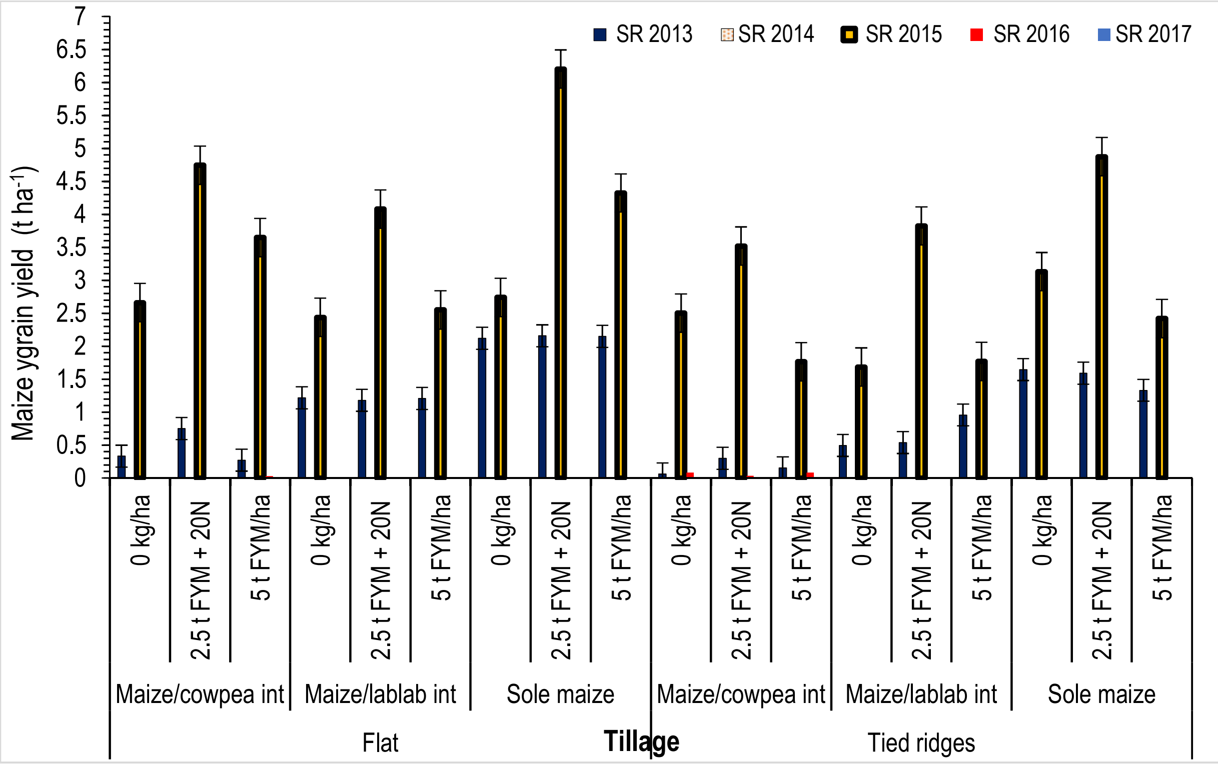

FIG. 12. Average maize grain yields under interactions of tillage, cropping systems and fertility treatments.

3.2.6. Biomass yields

The results of SR and LR maize biomass yields are summarized in Table 4. A significant difference in yield was found between fertiliser application treatments in both seasons (Figs. 13 and 14). The highest biomass yield was realized from plots with combinations of FYM and inorganic fertiliser. Significant difference in biomass yield was also found between cropping systems in the LR. Average biomass yield under interactions of cropping system and season is shown in Fig. 15.

Generally, the highest average maize biomass yield was obtained from sole maize systems (3.29 t ha^{-1}) compared to maize lablab intercrops (2.77 t ha^{-1}) and maize cowpea systems (2.53 t ha^{-1}). However, biomass harvested from intercrops when combined (maize plus legume) was higher in quantity and quality than from sole cropping systems.

TABLE 4. AVERAGE MAIZE BIOMASS YIELD (T HA^{-1}) DURING LR AND SR SEASONS (2013–2017)

Main effect	Treatment	Season	
		SR	LR
Tillage	Flat	3.96	1.78
	Tied ridges	3.66	1.59
	P value	0.408	0.537
	LSD	0.992	0.886
Cropping system	Maize / cowpea intercrop	3.54	1.27
	Maize / lablab intercrop	3.64	1.69
	Sole maize	4.25	2.09
	P value	0.08	< 0.001
	LSD	0.671	0.324
Fertility	Control	3.39	1.45
	FYM + N + P	4.45	1.86
	FYM	3.59	1.75
	P value	< 0.001	< 0.001
	LSD	0.377	0.174

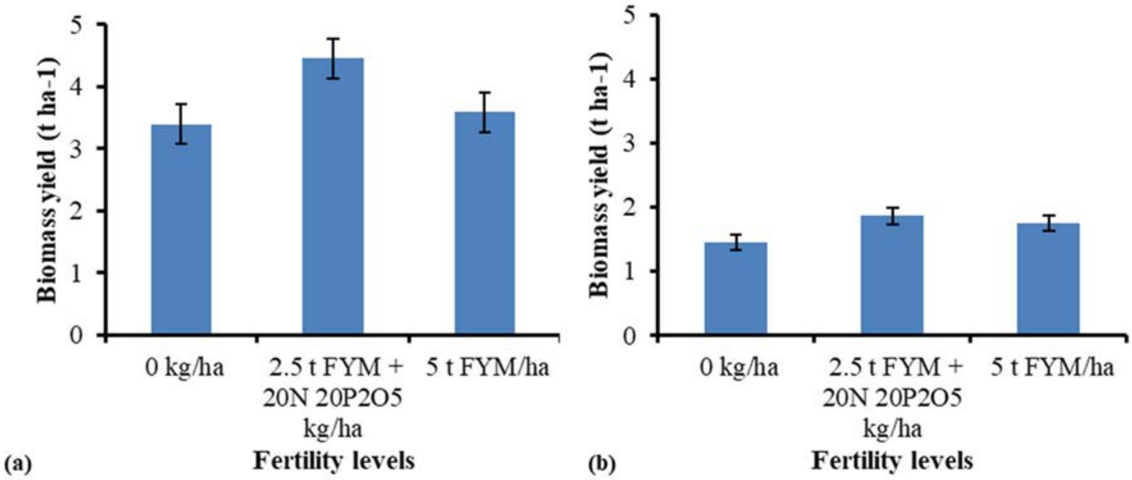

FIG. 13. Effect of fertiliser application on biomass yield in SR (a) and LR (b).

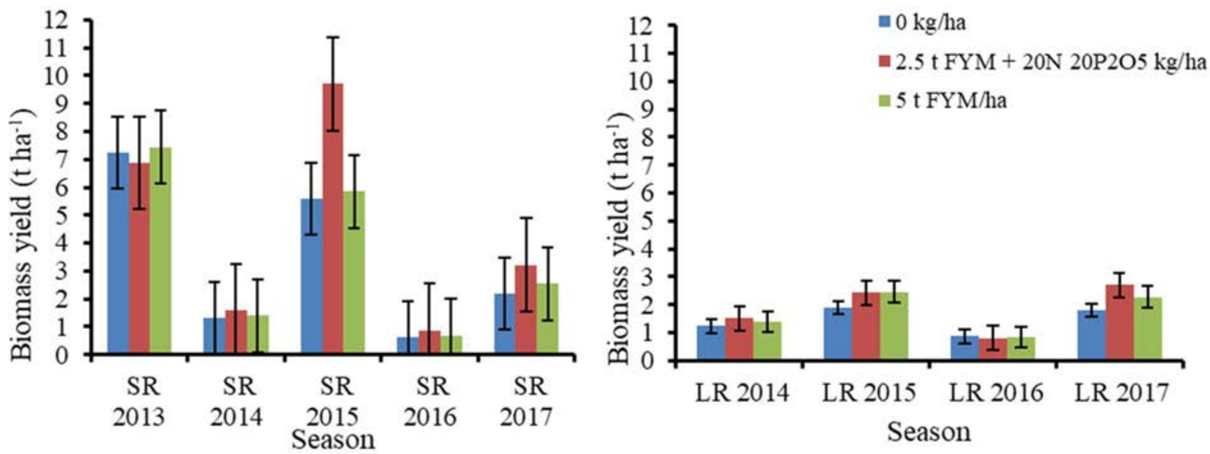

FIG. 14. Effect of interactions of cropping system and season on maize biomass yield.

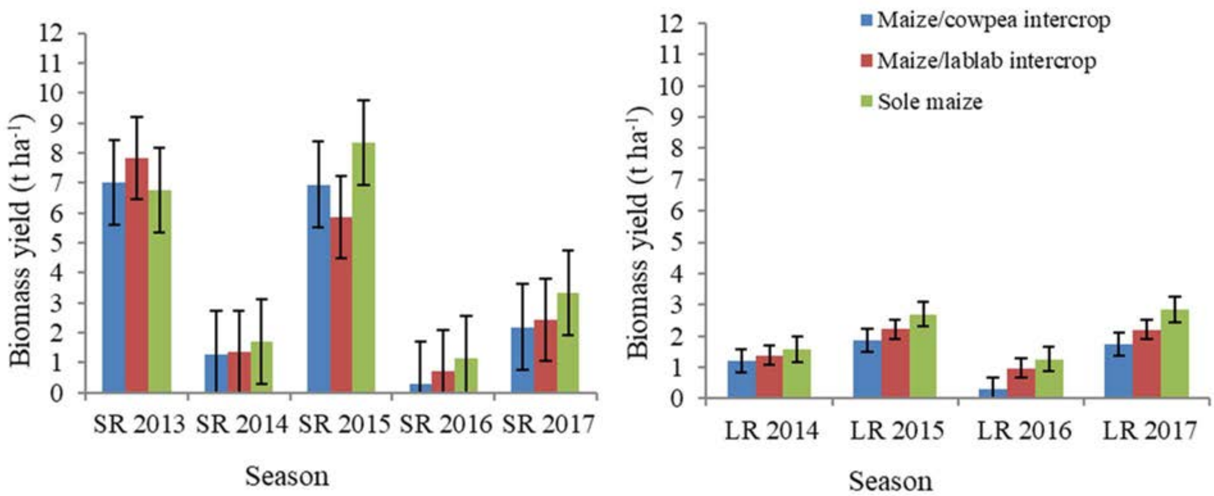

FIG. 15. Average biomass yields under different cropping systems during SR and LR seasons.

3.3. Cowpea

3.3.1. Grain yield

Cowpea grain yields under different treatments across the seasons are shown in Table 5. Unlike maize, and despite the low yields, cowpea grain was harvested at the end of every season. This indicates its adaptability to the low and poorly distributed rainfall conditions in the dry land.

3.3.2. Grain yields and effect of seasons and cropping systems

Analysis across the seasons and years indicated that yields recorded in different seasons were significantly different (P = 0.001) from each other (Fig. 16). This seasonal variation in yields was mainly attributed to the seasonal variation in rainfall.

The effect of cropping system is depicted by the high significant difference (P = 0.001) in yields from sole cowpea and maize-cowpea intercrop systems. Higher yields were obtained from sole cowpea plots (0.53 t ha^{-1}) compared to the intercrops (0.3 t ha^{-1}) (LSD = 0.101) indicating that intercropping maize with cowpea resulted in a reduction in cowpea yields. This was likely due to competition for resources, especially water. The highest yield in the sole cropped system was 1.21 t ha^{-1} whereas the highest in the intercropped system was 0.7 t ha^{-1}, both were in SR 2015 (Fig. 17). These seasonal variations resulted in significant difference between interactions of cropping systems with seasons where highest yields were obtained during SR 2015 in sole cowpea and the least (no yields) in LR and SR 2016. Reduction in yields in maize-cowpea intercrops has also been reported previously [18, 25].

TABLE 5. COWPEA GRAIN YIELDS UNDER DIFFERENT TILLAGE PRACTICES, CROPPING SYSTEMS AND FERTILITY DURING THE STUDY PERIOD (2013–2017)

Tillage	Cropping system	Fertiliser (ha^{-1})	SR seasons					LR seasons			
			13	14	15	16	17	14	15	16	17
Flat	Maize / cowpea intercrop	Control	0.65	0.00	0.04	0.16	0.68	0.21	0.40	0.00	0.40
		FYM+N+P	0.07	0.13	0.61	0.87	0.00	0.18	0.33	0.00	0.65
		FYM	0.65	0.65	0.00	0.05	0.16	0.15	0.40	0.00	0.59
	Sole cowpea	Control	0.97	0.17	1.18	0.15	0.19	0.23	0.42	0.98	0.65
		FYM+N+P	0.95	0.23	1.49	0.13	0.20	0.15	0.60	0.44	0.77
		FYM	0.87	0.20	1.37	0.13	0.18	0.18	0.47	0.24	0.80
Tied ridges	Maize / cowpea intercrop	Control	0.71	0.09	0.72	0.00	0.13	0.14	0.30	0.00	0.51
		FYM+N+P	0.57	0.10	0.78	0.00	0.18	0.16	0.31	0.00	0.63
		FYM	0.60	0.12	0.74	0.00	0.17	0.14	0.30	0.00	0.68
	Sole cowpea	Control	0.92	0.22	0.91	0.15	0.18	0.18	0.55	0.64	0.51
		FYM+N+P	0.78	0.21	1.25	0.19	0.33	0.17	0.56	1.08	0.68
		FYM	0.67	0.26	1.07	0.13	0.21	0.15	0.58	0.74	1.09

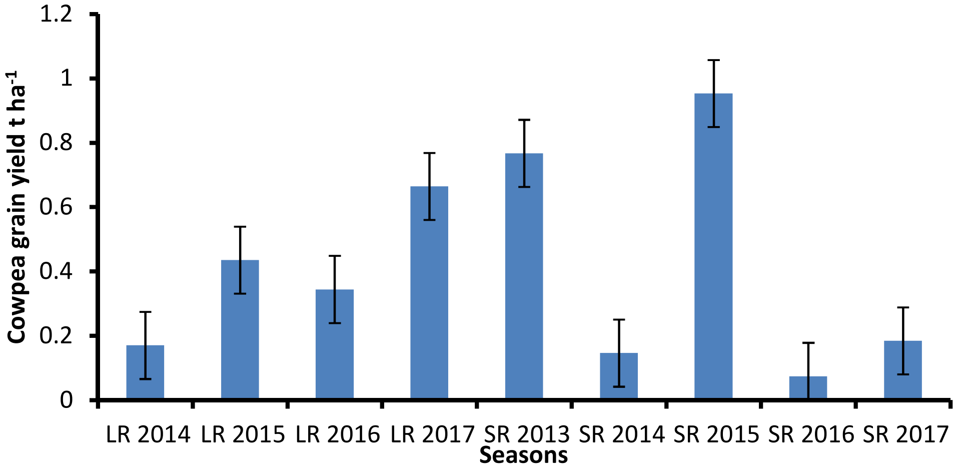

FIG. 16. Cowpea grain yield across LR and SR seasons.

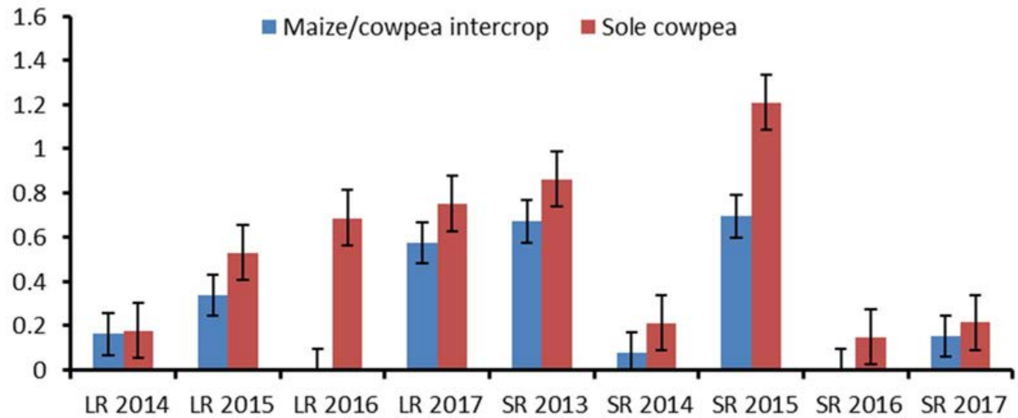

FIG. 17. Effect of cropping systems on cowpeagrain yield.

Results of analysis across similar seasons (LR or SR) are shown in Table 6. Significant differences in yields were found between cropping systems and seasons in both LRs and SRs.

TABLE 6. COWPEA GRAIN YIELDS UNDER DIFFERENT TILLAGE PRACTICES, CROPPING SYSTEMS AND FERTILITY IN LR AND SR SEASONS

Main effect	Treatment	Cowpea grain yield (t ha^{-1})	
		SR	LR
Tillage	Flat	0.437	0.385
	Tied ridges	0.412	0.421
	P value	0.780	0.788
	LSD	0.263	0.386
Cropping system	Maize/cowpea intercrop	0.320	0.269
	Sole cowpea	0.529	0.537
	P value	< 0.001	0.004
	LSD	0.040	0.062
Fertility	Control	0.409	0.383
	FYM + N + P	0.443	0.420
	FYM	0.423	0.407
	P value	0.223	0.471
	LSD	0.071	0.120

3.3.3. *Grain yields under tillage and fertility treatments*

No significant difference was found between different tillage systems or fertiliser application practices during both seasons. However, there were significant differences in interactions of cropping systems with fertility ($P = 0.046$) during SR where higher yields were realized from sole cowpea and combination of organic and inorganic fertiliser application (Fig. 18). In the LR seasons significant differences were found in interactions of tillage with fertility ($P < 0.038$) and of tillage with cropping system and fertility ($P < 0.037$). The effect of interaction of tillage with cropping systems and season ($P = 0.03$) during the LR is shown in Fig. 19. The effect of tillage alone was not significantly different across seasons.

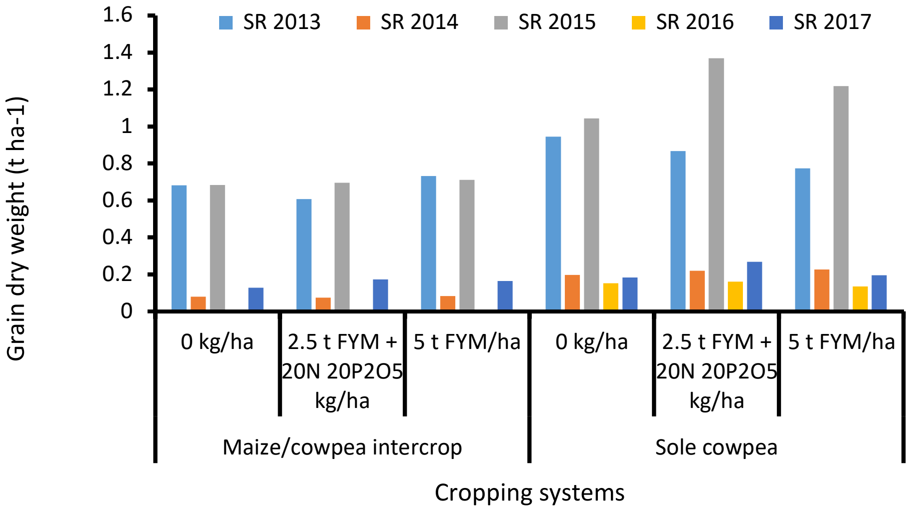

FIG. 18. Cowpea yields as affected by interactions of cropping systems with fertility in SR seasons.

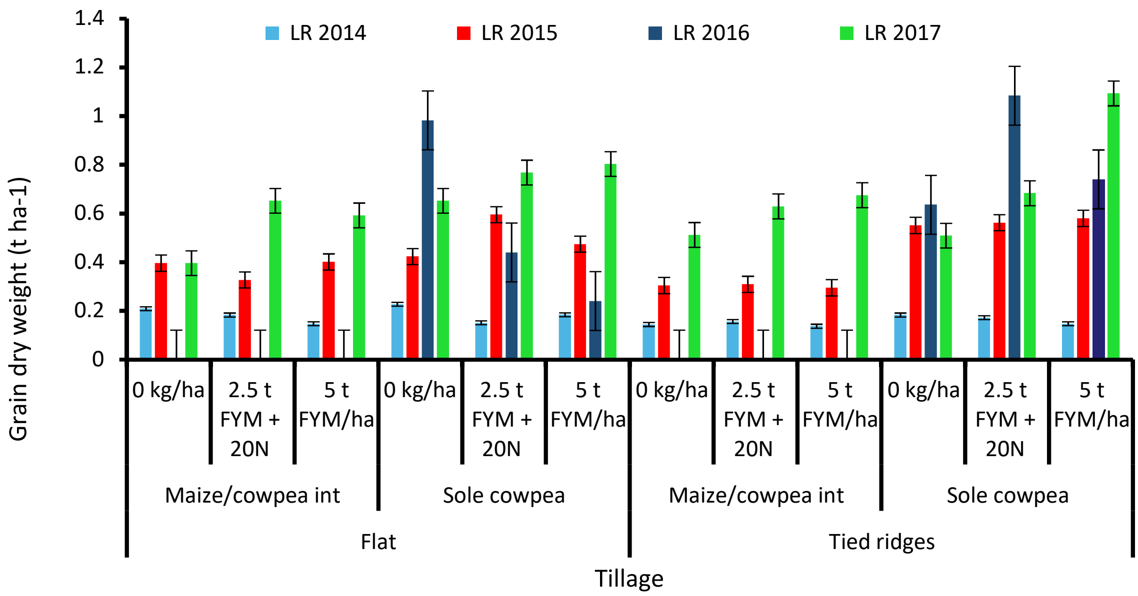

FIG. 19. Cowpea grain yield response to effect of interactions of tillage with cropping systems and fertility during the LR seasons.

3.3.4. *Biomass yield*

Biomass yields varied with seasonal rainfall conditions. Trends similar to those of grain yields were seen where significantly higher yields were obtained from sole crop systems than from the intercrops (Fig. 20). Higher yields were realized from the SR season as compared to the LR with highest yields harvested in SR 2015.

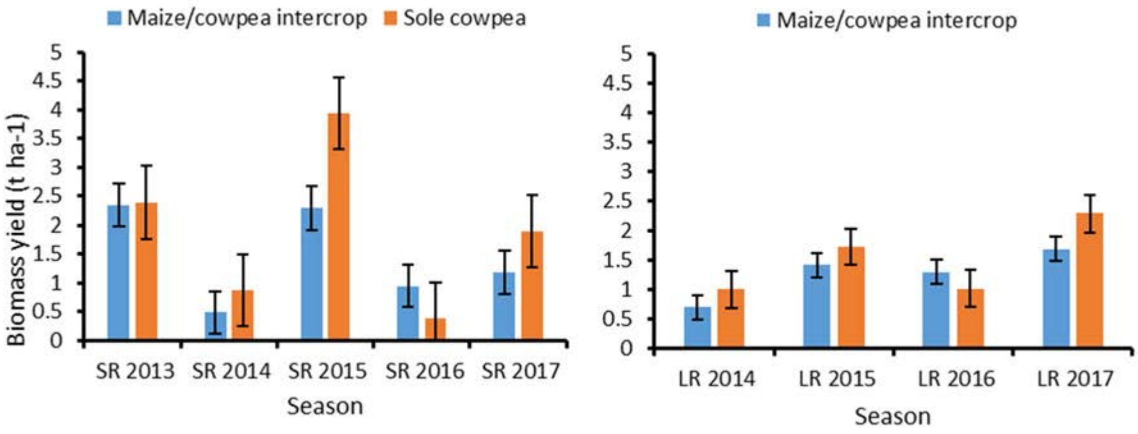

FIG.20. Cowpea biomass yield under different cropping systems.

When considering the effect of fertility, treatments with combinations of FYM and inorganic fertiliser gave higher yields both in the LR and SR (Fig. 21). Inorganic fertiliser boosted the effects of FYM and improved yields. The effect of FYM and inorganic fertiliser on biomass yield was therefore similar to that on grain yield.

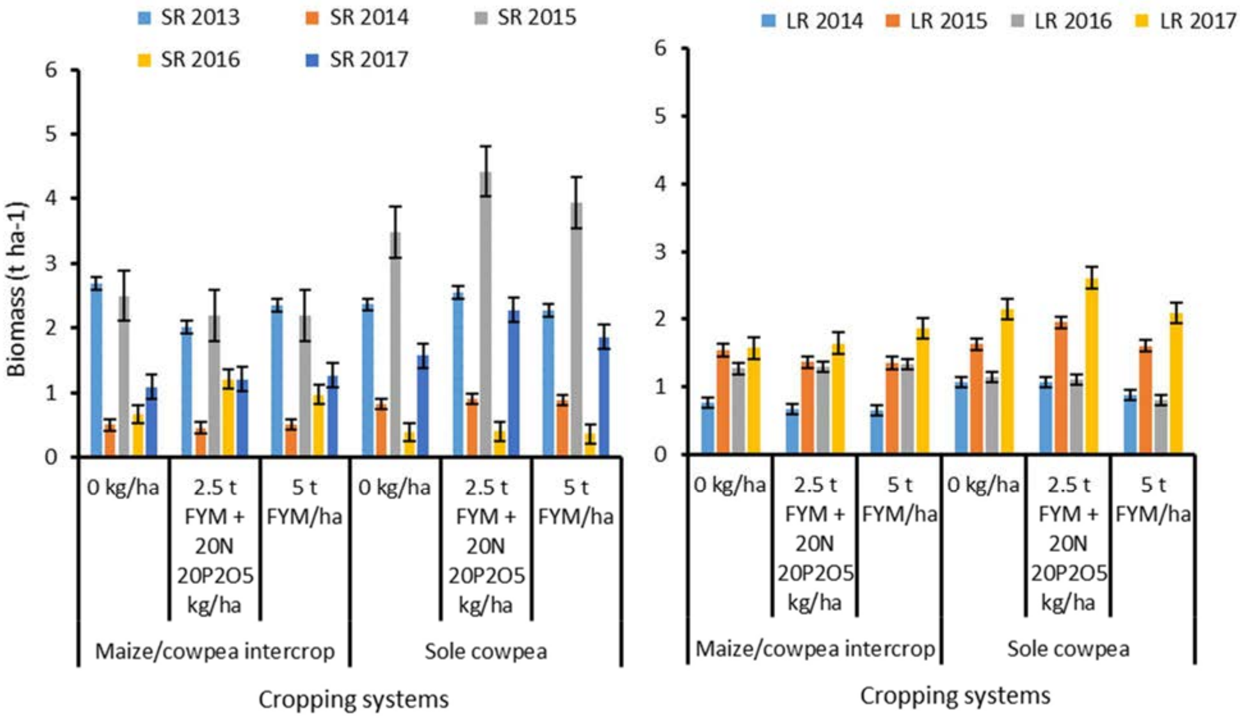

FIG. 21. Fertiliser effect on cowpea biomass yields.

Thus, cowpea grain and biomass yields were generally low and varied across the seasons and years. Such low and variable yields have been reported previously [18, 26] and could be attributed to variations in seasonal conditions. This is supported by slightly higher cowpea yields (0.95 t ha^{-1}) obtained in SR 2015 when rainfall distribution was fair.

3.4. LABLAB

3.4.1. Grain yield

Lablab grain was harvested at the end of each LR season. Low grain yields were realized due to poor rainfall distribution and dry spells. According to the Kenya government reports [27] dry spells make rain fed agricultural production in the ASALs of Kenya a risky enterprise due to the high chances of crop failure. This does not exclude drought tolerant crops such as lablab. Significant difference in yields were found between seasons ($P < 0.001$), cropping systems ($P = 0.016$) and interactions in cropping systems with seasons ($P < 0.001$) (Fig. 22). Sole crop systems produced higher grain yields than intercrops with highest yields harvested in LR 2016.

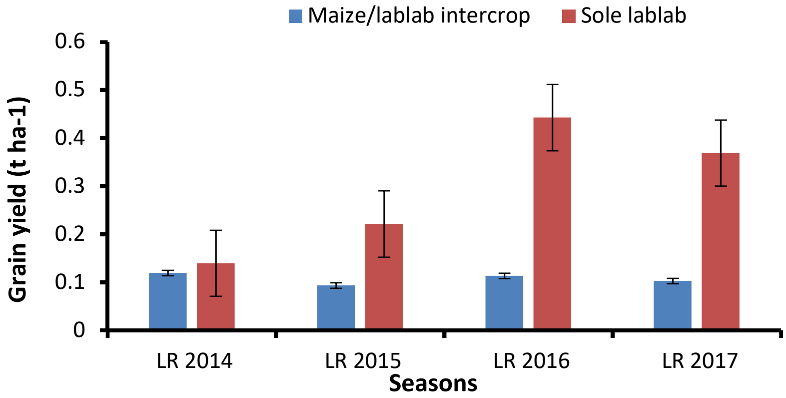

FIG. 22. Response of lablab grain to cropping systems.

Tillage or interactions of tillage practices were not significantly different across seasons (Fig. 23).

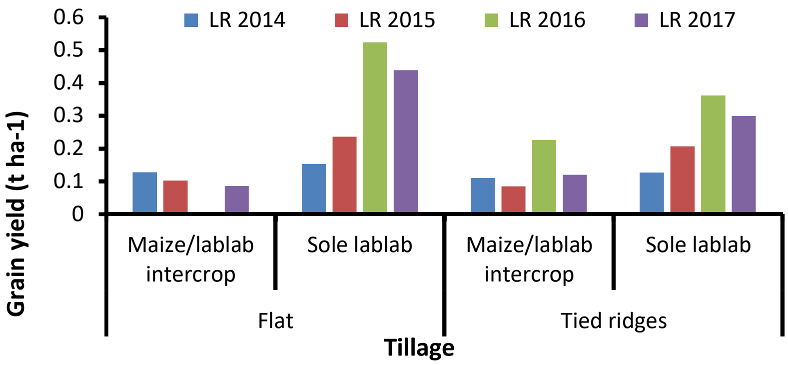

FIG. 23. Lablab grain yield under tillage with cropping systems interactions.

3.4.2. Biomass yield

Significantly higher biomass yield was harvested from sole crop systems than intercrops (Table 7). Higher yields (P = 0.041) were obtained from plots with the combination of FYM and inorganic fertiliser. No significant difference was found in the effect of tillage systems.

On average yields from intercrop systems were higher than from sole crop systems. However, when biomass yields are combined, harvests from intercropped systems (maize and legumes) were higher in quantity than those from legumes alone. These yields averaged across the years were 0.13 t ha^{-1} from sole lablab and 0.53 t ha^{-1} from sole cowpea as opposed to 0.62 and 0.79 t ha^{-1} from maize-lablab and maize-cowpea intercrops, respectively. Combined biomass from intercrops also gave more nutritious fodder as compared to those from sole crops.

TABLE 7. LABLAB BIOMASS YIELD UNDER DIFFERENT CROPPING SYSTEMS AND FERTILISER APPLICATION

Main effect	Treatment	Average biomass yield (t ha^{-1}) [a]
Cropping systems	Maize/lablab intercrop	1.68a
	Sole lablab	2.28b
	P value	0.016
	LSD	0.444
Fertility	FYM+N+P	2.15a
	FYM	1.90b
	Control	1.88b
	P value	0.04
	LSD	0.232

Note: [a] Different lowercase letters within a column denote significant differences ($P < 0.05$)

Yields also varied significantly with seasons (Table 8).

TABLE 8. LABLAB BIOMASS YIELD (T HA^{-1}) UNDER DIFFERENT FERTILISER APPLICATION PRACTICES AND SEASONS

Fertiliser application	Season								
	SR 2013	LR 2014	SR 2014	LR 2015	SR 2015	LR 2016	SR 2016	LR 2017	SR 2017
Control	5.20	3.213	0.64	1.03	3.57	0.83	0.28	1.40	0.79
FYM + N + P	6.57	2.14	0.79	1.03	4.38	0.80	0.66	1.63	1.38
FYM	4.77	3.08	0.81	1.20	3.67	0.63	0.51	1.36	1.03

4. CONCLUSIONS AND RECOMMENDATIONS

On-station field experiments involving maize under different fertility options planted in sole and intercropped systems (with cowpea or lablab) in conventional tillage or tied ridges at Katumani research farm revealed that grain and biomass yields varied significantly between seasons. Higher yields were obtained in the SRs than LRs. Knowledge of anticipated rainfall amounts and distribution through weather forecasts and updates is important for planning and management in climate-smart agriculture. Although increases in soil moisture with time and with depth of profile under tied ridges were evident, tillage practices did not affect yields significantly across the seasons. Their interactions with cropping system and seasons or fertility were however, considerable. This implies that tied ridges may be used cautiously in combination with other practices depending on the conditions of the season and soil types. Application of FYM micro-dosed with inorganic fertiliser at rates of 2.5 t FYM and 20 kg N + 20 kg P_2O_5 ha^{-1} significantly increased grain and biomass yields compared to FYM alone. Results also indicated that sole cropping and conventional tillage resulted in higher grain production. Higher yields and quality of biomass were obtained from intercropped systems. These technologies are required to be upscaled and out-scaled further in on-farm demonstrations to assist farmers improve production for household food and animal feed security.

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CONTRIBUTION OF INTEGRATED CROPPING-LIVESTOCK SYSTEMS TO SUSTAINABILITY OF AGRICULTURAL SYSTEMS IN ARGENTINA

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Abstract

The predominance of continuous cropping systems (CC) and their simplification due to the high proportion of soybean is the main concern related to the sustainability of agricultural systems in Argentina. The combination of no tillage and pastures in integrated cropping-livestock systems (ICLS) is a useful practice to enhance soil organic carbon (SOC) levels compared to CC, especially in the context of climate change. Our objectives were to compare SOC and its physical fractions in ICLS and CC, and evaluate the use of δ13C to identify the source of SOC in these systems in the Pampas region of Argentina under farm conditions. We compared two farms, an ICLS and a CC, which shared the same soil type (Typic Haplustoll/Luvic Phaeozem) and were in the same landscape position. The ICLS farm produces lucerne (Medicago sativa Merrill) and oat (Avena sativa L.) grazed by cattle alternatively with a grain summer crops sequence of soybean (Glycine max L.) and corn (Zea mays L.), while the CC farm produces soybean and corn in a continuous sequence. In both farms, the same management has been carried out for more than 20 years. Replicated (n = 3) soil samples were collected from different soil depths (0–5, 5–20, 20–40 and 40–60 cm) and analysed for SOC, its physical fraction and their isotopic signature (δ13C). Soils under ICLS showed an increment of 50% of SOC stocks compared to CC in the first 60 cm. This increase was related to <50 and 100–2000 μm fractions of SOC. The shift in δ13C signature was more in ICLS compared to CC suggesting that rotation with legumes contributed to C sequestration. At 5–20 cm, δ13C signature were –17.6 ‰ in ICLS and –17.3 ‰ in CC. Systems having a perennial forage component are likely to show an increase in C sequestration, a process that can improve soil quality and the resilience of crop production. The use of δ13C is useful to identify the source of this increase and therefore to help farmers' perceptions about the importance of perennial pastures to soil health and climate smart agriculture.

1. INTRODUCTION

Declining soil fertility and quality because of poor farming practices and changing climate is an immense threat to sustainability of crop production. To meet the growing demand of the increasing human population and enhance soil fertility, quality and health, an integrated cropping-livestock system (ICLS) has been proposed as one of the best farm management practices. Among the benefits of ICLS are the better synchronization of biogeochemical cycles due to the alternation of pastures and crops, the increase in farm resilience to adverse climatic and economic events, and the promotion of the many ecosystems services they can provide [1, 2].

Among these ecosystems services, the increment of soil organic carbon (SOC) contributes to improve soil quality and mitigate climate change. Forages have extensive, fibrous, root systems that explore large volumes of soil deeper than most grain crops. Perennial forages also extend the growing season compared with annual cash crops, thereby photosynthesizing, depositing rhizosphere C inputs, and consuming soil water during longer periods than annual crops. This extended growth period likely contributes to soil C sequestration. Another key factor is that perennial forages remain without soil disturbance for several years. Lack of soil disturbance may be vital for ICLS to enhance SOC accumulation rather than simply to maintain it [3].

In the Humid Pampas, the most important farming region of Argentina, the replacement of natural vegetation into farming systems and their oversimplification due to the high soybean proportion in the crop sequence has been the main cause of environmental degradation [4]. This process mainly produces a decline of the SOC content and an increase of the soil erosion risk over the last century [5, 6]. Fortunately, currently most of the continuous cropping systems (CC) in Argentina are under no tillage [7], which contributes to the soil erosion reduction [8], but limits the C sequestration due to the oversimplification of the crop sequence [9]. In this sense ICLS soils have a high potential to store additional amounts of SOC as degradation by agricultural uses have caused C losses in the past [10].

Robust data to generalize responses from this contrast in farming styles remain to be collected from a variety of regions around the world, especially at the farm level, which provides a more realistic estimation of the impact of the integration of livestock and crops than the plot level. In addition, the study of the different fractions and the use of isotopic techniques allow researchers to obtain a better understanding of the dynamics of SOC improvement [11, 12]. Thus, our objectives were to compare SOC and its physical fractions in ICLS and CC, and evaluate the use of $\delta^{13}C$ to identify the source of C in SOC in these systems in the Pampas region of Argentina under actual farm conditions.

2. MATERIALS AND METHODS

2.1. Site Description

The study was conducted near to the city of Venado Tuerto, in Santa Fe province, Argentina (33°39'S; 62°10'W), which is located in the Humid Pampas Eco region. The mean annual temperature is 16°C and the mean annual precipitation is 950 mm [13]. Soils developed on Holocene loessal sediments are predominately Mollisols [14]. Continuous cropping under no tillage is the main farming system, in which soybean (*Glicine max* L.) and maize (*Zea mays* L.) are the main crops [15]. Integrated cropping-livestock are grazed on temperate pasture, mainly lucerne (*Medicago sativa* Merrill), which is extensively grazed by, steers, allowing beef production higher than 800 kg ha^{-1} y^{-1} [16].

2.2. Experimental Design, Treatments and Field Management

Two farms inside the same soil cartographic unit and landscape position in the region were compared (Fig. 1). The soil is classified as a Typic Haplusdoll (Luvic Phaeozem) [17]. Soil texture and soil bulk density of the upper horizon are shown in Table 1.

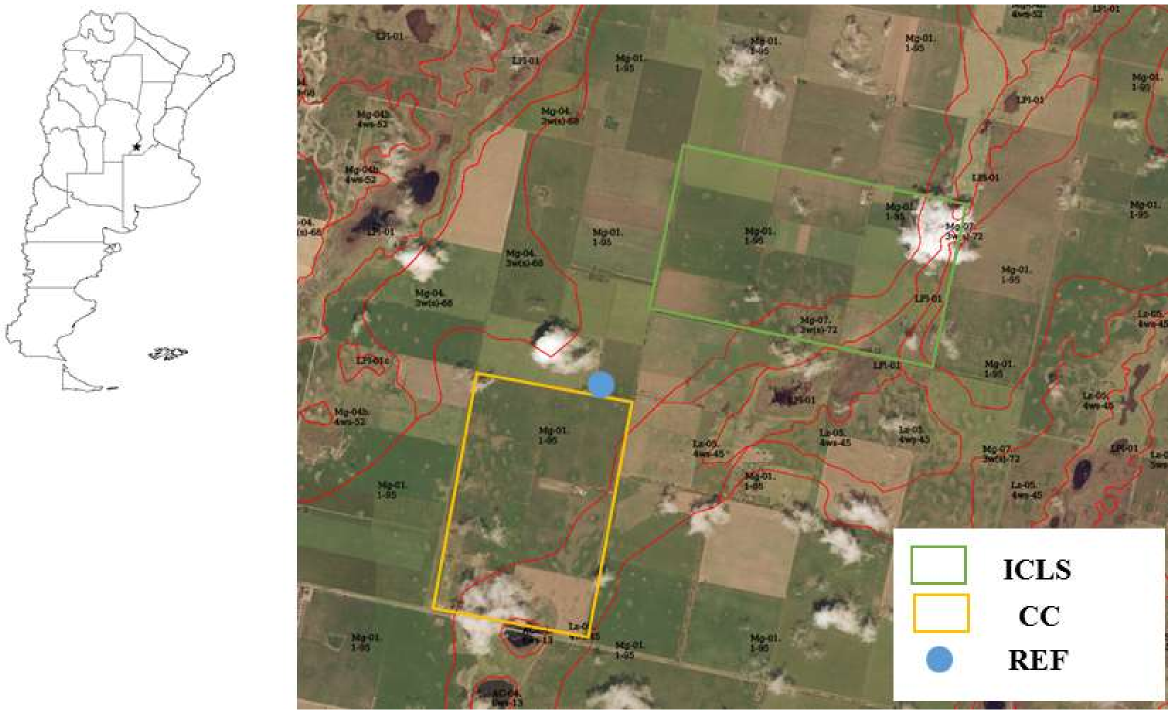


FIG. 1. Geographical location of the study. ICLS: limits of the integrated crop-livestock farm, CCS: limits of the continous cropping farm. Soil cartographic units at 1:50000 (INTA, 2015). Mg-01. 1-05: Maggiolo soil series (Typic Hapludoll).

The ICLS farm produces lucerne and oat (*Avena sativa* L.) grazed by cattle alternatively with grain summer crops sequence of soybean and maize, and the farm under continuous cropping (CC) produces soybean and corn in a continuous sequence. In addition, we selected a third site under natural vegetation to have as a reference soil (REF).

TABLE 1. BULK DENSITY AND PARTICLE SIZE DISTRIBUTION IN COMPOSITE SAMPLES IN CONTINUOUS CROPPING FARM (CC), INTEGRATED CROPPING-LIVESTOCK FARM (ICLS) AND REFERENCE SOIL UNDER NATURAL VEGETATION (REF)

Treatment	Bulk density	Particle size distribution (g kg^{-1})		
	(g cm^{-3})	Clay	Silt	Sand
CC	1.3	360	330	310
ICLS	1.3	340	260	400
REF	0.8	310	400	280

2.3. Soil Sampling and Analytical Determination

Soil was sampled before the planting of summer crops in the spring of 2014. Triplicate random samples were taken using a soil probe at the following soil depth: 0–5, 5–20, 20–40 and 40–60 cm. At deeper depths, we found the presence of a water table. Samples were air dried and passed through a 2 mm sieve. The physical fractionation of organic C was carried out, from which the following fractions were obtained: coarse particulate organic carbon (POCc, 100–2000 µm), intermediate particulate organic carbon (POCi, 50–100 µm) and mineral organic carbon (MOC, <50 µm) according to [18]. The technique consisted of suspending 30 g of soil in 120 ml of distilled water. In order to make a homogeneous suspension, three small spheres of glass were used in a mechanical agitator for 4 h. The wet sieving was carried out with a vibration sieve (FRITSCH Analysette 3 PRO). The different fractions were dried in an oven at 60°C until stable weight. Organic carbon (OC) was determined using the Walkley and Black procedure [19].

The $\delta^{13}C$ is an expression of the natural abundance of the isotope in relation to a laboratory reference material calibrated against an international standard. The measurement of $\delta^{13}C$ was carried out using an isotope-ratio mass spectrometer (EA-IRMS) and normalization of $\delta^{13}C$ results was performed on the L-SVEC-NBS-19 scale, according to [20]. $\delta^{13}C$ is expressed in units of per thousand (‰) and is calculated using equation 1.

$$\delta^{13}C\ (‰) = \left[\frac{R_{sample} - R_{PDB}}{R_{PDB}}\right] \times 1000 \qquad (1)$$

Where:

$R_{sample} = {}^{13}C/{}^{12}C$ is the isotope ratio in the sample.

$R_{PDB} = {}^{13}C/{}^{12}C$ is the isotope ratio in the international standard Pee Dee Belemnite (PDB).

2.4. Data Analysis

The three land uses: CC, ICLS and REF were compared assuming the same soil type and landscape position [21]. SOC data at each depth were subjected to an analysis of variance (ANOVA) using Infostat v. 2014 [22]. Differences among treatment means were examined using the least significant difference test (LSD) at the 5% level of probability.

3. RESULTS AND DISCUSSION

3.1. Total Soil Organic Carbon Content

The vertical distribution of SOC in the soil profile among land uses is shown in Fig. 2. The SOC content was REF>ICLS>CC at 0–5 and 5–20 cm ($P<0.05$). At 20–40 cm REF=ICLS>CC and at 40–60 cm there were no differences among treatments. The main differences in SOC were observed in the first 20 cm, probably due to the effect of carbon derived from the roots. These results agreed with pasture-crop rotations in Europe and America [23, 24]. The deeper roots of alfalfa can explain the effect at 20–40 cm. It has been shown that the type of vegetation root system affects the vertical distribution of SOC [25–26].

The SOC stock to 60 cm was 102 Mg ha^{-1} in REF, 93 Mg ha^{-1} in ICLS and 62 Mg ha^{-1} in CC ($P<0.05$). This equates to an increment of 50% in SOC stocks from the conversion of CC into ICLS. The large gain in SOC with establishment and maintenance of perennial pastures seems a key mitigation strategy to climate change offered by ICLS. In this sense, ICLS could be a viable strategy to overcome the limitations in the ability of agriculture under no-tillage to sequester SOC, and therefore establish adequate international policy [27, 28].

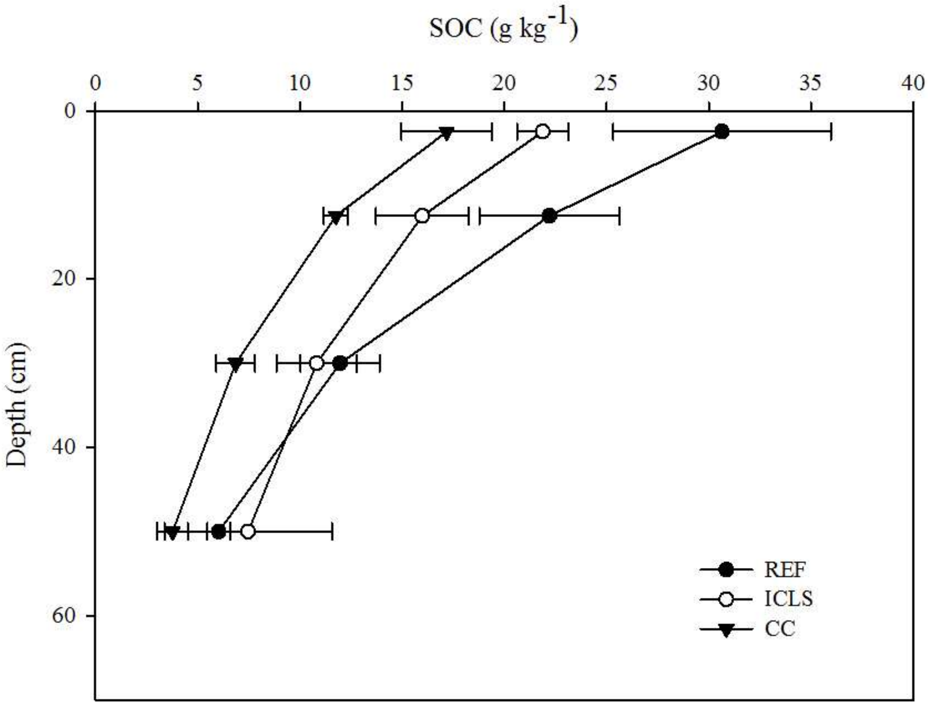
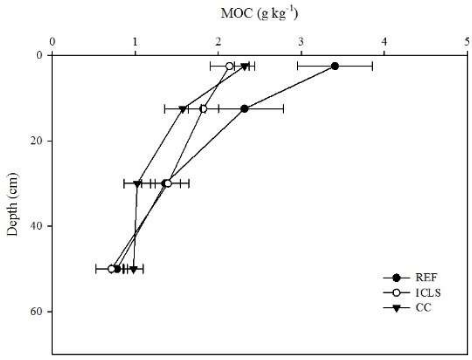


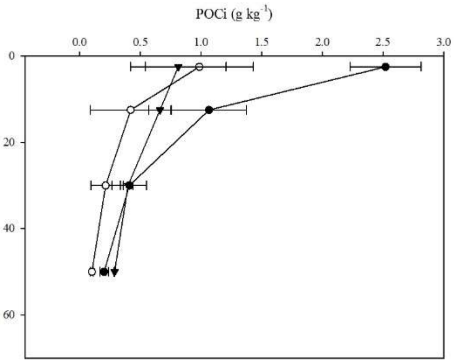
FIG. 2. Vertical distribution in the soil profile of soil organic carbon (SOC) among different land uses: integrated cropping-livestock system (ICLS), continous cropping system (CC) and a reference soil (REF). Horizontal bars represent standard deviation (n = 3).

3.2. PHYSICAL FRACTIONATION OF SOC

The vertical distribution in the soil profile of MOC, POCi and POCc among land uses is shown in Fig. 3. There was a greater accumulation of POCi in REF compared to ICLS and CC ($P<0.05$) in the superficial layer (0–5 cm). According to [12], levels of POC are directly related to the input of plant residues in soil. No differences were detected between ICLS and CC in POCi unlike [12], although these authors analysed POCc and POCi together. Therefore, the carbon coming from the surface residues is similar between ICLS and CC. The POCc fraction was similar between CC and ICLS in the first 20 cm, while at 20–60 cm ICLS was greater than CC ($P<0.05$). This means that the most active fraction of organic C was only sensitive within the subsoil, probably because of a greater root system. There was a greater accumulation of MOC in REF compared to ICLS and CC ($P<0.05$) in the superficial layer (0–5 cm), reflecting the low influence of management on the formation or rupture of aggregates under 53 µm.



(a)



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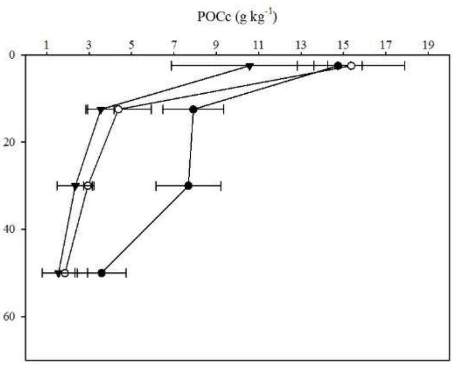


(c)

FIG. 3. Vertical distribution in the soil profile of a) mineral organic carbon (<50 µm, MOC), b) intermedium particulate organic carbon (50–100 µm, POCi) and c) coarse particulate organic carbon (100–2000 µm, POCc) among different land uses: integrated cropping-livestock system (ICLS), continous cropping system (CC) and a reference soil (REF). Horizontal bars represent standard deviation (n = 3).

3.3. Isotopic Determination

3.3.1. Total soil organic carbon

The $\delta^{13}C$ signatures varied among the three land uses and were higher for REF and ICLS compared to CC (Fig. 4). The $\delta^{13}C$ signatures in 0–5 cm for REF, ICLS and CC were –20.1, –20.0 and –19.8 ‰ respectively; while the values in the 5–20 cm soil depth for these treatments were –17.9, –17.6 and –17.3 ‰ respectively. The fractionation, which occurs during CO_2 uptake and photosynthesis, depends on the type of plant and the climatic and ecological conditions. The Hatch-Slack photosynthetic pathway (C_4) results in $\delta^{13}C$ signatures of −10 to −15 ‰ and is primarily represented by certain grains and desert grasses (sugar reed, corn). In temperate climates, most plants employ the Calvin mechanism (C_3), producing $\delta^{13}C$ values in the range of −26 ‰ [29]. These results agreed with previous research in the same sites and reflect a higher proportion of C_3 species in the crop sequence due to the incorporation of lucerne and oat [30].

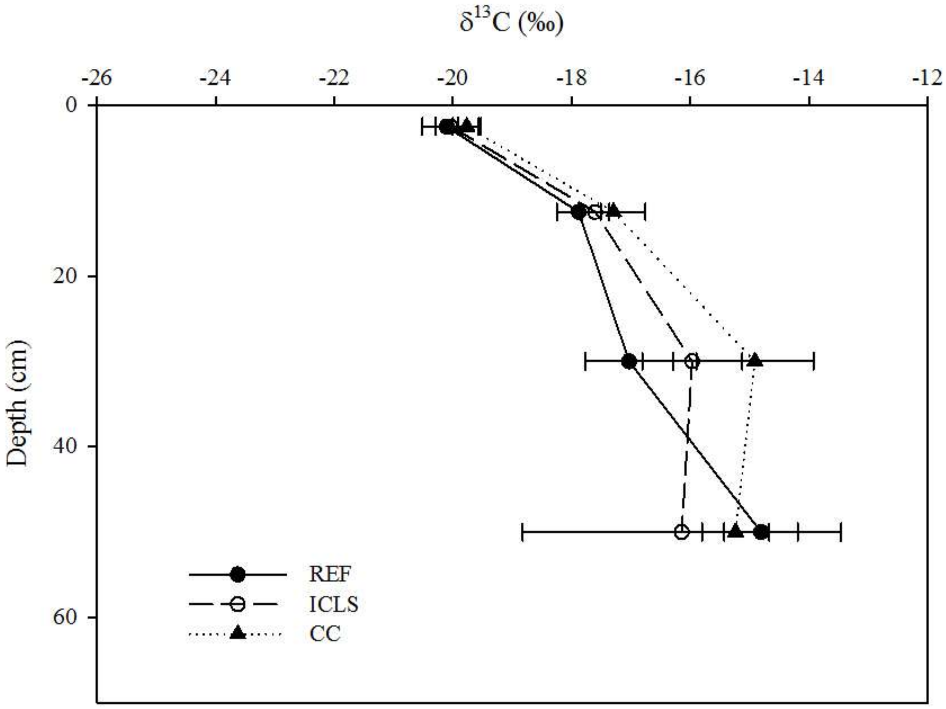
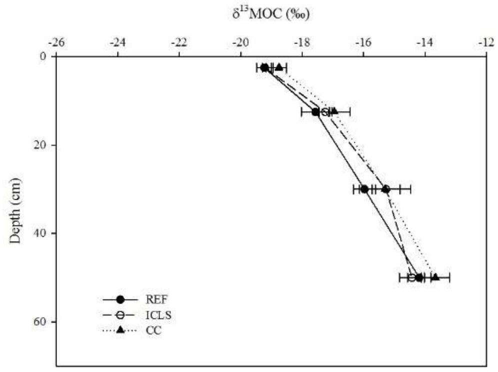


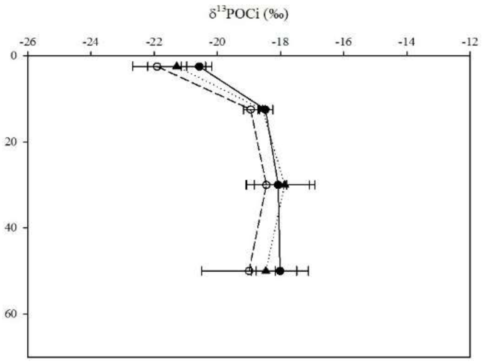
FIG. 4. Vertical distribution in the soil profile of of δ13C natural abundance in soil organic carbon (SOC) among different land uses: integrated cropping-livestock system (ICLS), continous cropping system (CC) and a reference soil (REF). Horizontal bars represent standard deviation (n = 3).

3.3.2. Particulate soil organic carbon

The vertical distribution in the soil profile of $\delta^{13}C$ among the MOC, POCi and POCc fractions is shown in Fig. 5. The $\delta^{13}C$ natural abundance in MOC was higher in CC (−18.7 ‰) than in ICLS and REF (−19.2 ‰) at 0–5 cm. This suggests a high proportion of C derived from C_3 in ICLS and REF. In this fraction there were no differences among land uses in the other depths, with a tendency of higher values at deeper depths. With respect to POCi, there were differences among treatments at 40–60 cm, at which REF>ICLS>CCS. In relation to POCc, the differences among treatments were detected at 20–40 cm, at which REF>ICLS=CC. It was also observed that the lower values of $\delta^{13}C$ are found in MOC than POCi and POCc which may be related to the lower rate of decomposition of MOC and the protection of ^{13}C. In turn, in the MOC fraction an enrichment of ^{13}C at depth was observed, due to the lower disturbance in the soil, decreasing the decomposition rate of carbon [31].



(a)



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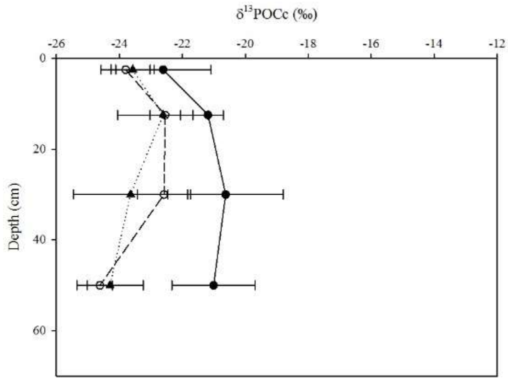

(c)

FIG. 5. Vertical distribution in the soil profile of $\delta^{13}C$ natural abundance in a) mineral organic carbon (<50 µm, MOC), b) intermedium particulate organic carbon (50–100 µm, POCi) and c) coarse particulate organic carbon (100–2000 µm, POCc) among different land uses: integrated cropping-livestock system (ICLS), continous cropping system (CC) and a reference soil (REF). Horizontal bars represent standard deviation (n=3).

4. CONCLUSION

ICLS under no tillage improved SOC levels due to higher plant residue inputs derived mainly from pasture as compared to CC. Systems having a perennial forage component are likely to promote C sequestration, a process that can improve soil quality and the resilience of crop production. The use of $\delta^{13}C$ is useful to identify the source of this increase and therefore to help farmers' perception about the importance of perennial pastures to soil health and climate smart agriculture. Our results showed that $\delta^{13}C$ signatures identified the sources of C inputs in soil and ICLS improved soil quality and health by exhibiting significantly higher amount of C in the 0–40 cm soil depth.

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COMPARATIVE EFFECT OF MAIZE CULTIVATION-CATTLE GRAZING ROTATION ON SELECTED FERRALLITIC SOIL PROPERTIES AND MAIZE YIELD IN THE LAKE VICTORIA CRESCENT

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Abstract

Integrated cropping-livestock systems on a single farm, is seen as the sine qua non pathway for addressing the challenge of increasing land productivity and sustainability of minimum input small-scale African farming systems. However, the yield gap between this system and the fertilized system is not known for most of the soils and crops. This study therefore i) assessed the effect of maize cultivation cattle grazing rotation on maize yield and plant nutrient uptake; ii) assessed the effect of maize cultivation cattle rotation on selected physical and chemical properties of ferralitic soils in Uganda; and iii) assessed farmers constraints to quality livestock fodder access and improvement. A completely randomised block design experiment was conducted on-farm between 2015 and 2017 for five seasons. Four treatments were considered, namely: Continuous maize, maize rotation with grazing, bare ground, and continuous grazing. In addition, a household survey was conducted among livestock farmers to assess the constraints they face in accessing and improving livestock fodder. The maize grazing rotation significantly reduced the gap between fertilized and unfertilised maize yield on ferralitic soils of Uganda ($P<0.05$). In comparison with the manure applied to the soil potassium and calcium content in maize biomass and soil significantly increased compared with inorganic fertiliser ($P<0.05$). In light of the above results when access to nitrogen, phosphorus, and potassium (NPK) fertiliser is limited, we recommend the use of the maize-grazing rotation for a better maize yield on ferralitic soils of central Uganda. Livestock fodders are plentiful but farmers mainly depend on unimproved pastures.

1. INTRODUCTION

Integrated cropping-livestock systems (ICLS) are highly recommended systems [1] because of their minimal adverse effects on the environment [2, 6] and the positive economic and agriculture production outcomes [7]. ICLS are designed to achieve synergisms that result from interactions in the soil-plant-animal-atmosphere system [8]. These systems can be carried out in the same area concurrently, sequentially in rotation or in succession [8]. They are a dominant source of livelihood supporting over 80% of people living in the developing world and producing 50% of world cereals, around 34% of the global beef production and about 30% of global milk production [9] hence contributing significantly to the global development agenda [10].

In East Africa, Kenya is recognized among developing countries for its success in integrating dairy into smallholder farming systems, through which returns are maximized from limited land and capital [11]. The most common animals and crops used under integrated systems are cattle and maize respectively. Crop-livestock integration is important in Uganda because of the low inorganic fertiliser use in order to maintain the fertility of the soil used continuously for crop cultivation, if farms have to be more commercial and market oriented. Pender et al. [12] reported that less than 10% of smallholder farmers in Uganda apply inorganic fertiliser but at a very low application rate of 1 kg of NPK ha^{-1}. The low use of fertiliser and their low application rate in Uganda is attributed a high cost: 1 kg of NPK costs about 1 US$, while diammonium phosphate (DAP) is even more expensive [13] which is not affordable to many farmers, and there is limited awareness [14, 15]. Subsequently continuously cultivated soils in Uganda have the highest rate of nutrient depletion. Nkonya et al. [16] observed that soil nutrient depletion in Uganda is one of the leading environmental degradation problems threatening the livelihoods of most small-scale farmers in the region. They observed that only 5% of the sampled households had positive total NPK balances. According to Wortman and Kaizzi [17] about 70 kg ha^{-1} of nitrogen (N), phosphorus (P) and potassium (K) are lost annually from cultivated land in Uganda. Although ICLS is recognised as one of the practices which can contribute to sustainable land productivity, there is still limited evidence on its effects on crop yield and soil health indicators. This study therefore i) assessed the effect maize cultivation-cattle grazing rotation on maize yield and plant nutrient uptake and ii) assessed the effect of maize cultivation-cattle rotation on selected physical and chemical properties of ferralitic soils in Uganda.

2. MATERIALS AND METHODS

2.1. Study Sites

The experiment was conducted on-farm in Nkokonjeru sub-county in Mukono District. Mukono district is located in Central Uganda at 22 km on the Kampala-Jinja Road 021'11.999" N and 3245'19.080" E. it shares borders with the District of Buikwe in the east, Kayunga along the river Sezibwa in the north, Luwero in the north west, Kampala and Wakiso in the south west, Tanzania, Lake Victoria in the south with the Islands of Buvuma District. It has a population of about 551000 people of whom 49.8 and 50.2% are male and female respectively. Its population is growing at a rate of 2.7% per annum. The major soils in Mukono District are Ferralsols. The mean annual rainfall is 11000 mm distributed over 106 rain days, with peaks in March–May and September–November. Temperatures range between 16 and 28° C throughout the year.

Two sites were selected based on the reconnaissance visit conducted in 2014, and two farmers located near each other on the same soil type were selected to host the experiment. A second visit was successfully conducted to brief the preselected farmers about the study and to request their involvement by provision of land to commit themselves to managing the experiments. Two soil samples were taken per site from the depths of 0–15 and 15–30 cm for site characterization of the soil fertility attributes and were analysed at Makerere University for physico-chemical properties (Table 1). Generally, the soils of the two sites have adequate pH for crop growth, the level of organic matter is generally high, but values of N, P and K, and bases such as Ca and Mg are relatively low.

TABLE 1. CHARACTERISTICS OF THE SOILS AT THE TWO SITES

			Total (g kg^{-1})			Exch. cations (cmol$_c$ kg^{-1})				Texture (g kg^{-1})		
Sample	Depth (cm)	pH	N	OM	Bray 1 P (mg kg^{-1})	K	Ca	Mg	Na	Sand	Clay	Silt
Site 1	0–15	5.5	1.20	32.1	6.92	0.18	2.67	0.34	0.078	410	290	290
Site 1	15–30	5.5	1.19	30.8	6.88	0.15	2.98	0.31	0.085	420	300	280
Site 1	0–15	5.9	1.80	32.1	1.22	0.13	4.21	0.23	0.063	450	310	240
Site 1	15–30	5.6	1.53	28.9	2.56	0.17	2.97	0.48	0.142	470	300	230
Site 2	0–15	6.0	1.22	36.8	5.23	0.24	4.76	0.62	0.231	500	260	240
Site 2	15–30	5.9	1.77	27.6	1.35	0.11	2.35	0.31	0.022	520	280	200
Site 2	0–15	5.7	1.63	34.2	6.51	0.22	4.75	0.27	0.174	500	220	280
Critical value		5.5–6.5	2.20	30	15	0.34	1.75	0.60	<1			

2.2. Experimental Design, Treatments and Replications

A completely randomized block design was adopted. The field experiment was set up at the onset of the first rain season (MAM-2015) on two preselected farms constituting sites 1 and 2. At each site, four treatments were set up namely: Maize continuous (every season, maize was planted in the same plots); maize rotation with grazing (in this plot maize was only planted after being used for grazing); bare ground (neither crop nor other plants including weeds were allowed to grow); and grazing continuous (these plots were under continuous grazing every season). At each site, each of the treatments was replicated twice. Only four plots were planted with maize for the four (maize continuous and maize/grazing). The variety of maize used is Longe 5. Prior to planting, all the plots including the bare and grazing ones were blanket fertilized with 120 kg ha^{-1} of NPK 17:17:17 through broadcasting in 2015. The experimental sites were fenced off, and the plots under continuous grazing and maize grazing rotation were fenced off with poles and barbed wires from other plots. Soil and plant samples were collected for each of the seasons and taken at Makerere University, soil and water laboratory at the Department of Agricultural Production for analysis.

2.3. Data Analysis

Both soil and plant yield and nutrients contents were analysed in Genstat discovery for separation of means for $P \leq 0.05$.

3. RESULTS AND DISCUSSION

3.1. Effect of Maize Cultivation-Cattle Grazing Rotation on Maize Yield and Plant Nutrient Uptake

The comparative effect of maize cultivation and cattle grazing on maize biomass yield is shown in Table 2. Maize continuous fertiliser had relatively high biomass followed by maize grazing on average for the five seasons of data collection. However, significant difference in biomass was observed only in terms of biomass production between maize continuous-fertilised and maize-continuous ($P < 0.05$). Generally, MAM tended to have more maize biomass compared to SON for all the three treatments ($P < 0.05$).

TABLE 2. AVERAGE EFFECT OF MAIZE-GRAZING ROTATION ON MAIZE BIOMASS YIELD (T HA^{-1}) FROM SON 2015 TO MAM 2017

Treatment	MAM	SON	Average
Maize Continuous-Fertilised (MCF)	14.52 a	10.42 a	12.47
Maize-Grazing (MG)	12.59 ab	10.27 a	11.43
Maize-Continuous (MC)	11.37 b	8.34 b	9.56
Average	12.83	9.67	11.25

Note: Data within a column followed by different lower-case letters are significantly different ($P < 0.05$)

The comparative effect of maize-grazing rotation on maize grain yield is shown in Table 3. As for biomass, maize continuous fertilised had on average a relatively high yield followed by maize-grazing rotation. However, statistical differences in grain yield were only observed between maize continuous fertilised and maize continuous with no fertiliser application ($P < 0.05$). As observed for biomass, MAM grain yields were relatively higher than SON maize grain yield ($P < 0.05$). No significant difference was observed between treatments during SON ($P > 0.05$). It is worthwhile to note that the maize grain yield was significantly higher than farmers' yield and was close to the maximum yield for the variety in the study agroecological zone.

TABLE.3. AVERAGE EFFECT OF MAIZE–GRAZING ROTATION ON MAIZE GRAIN YIELD (T HA^{-1}) FROM SON 2015 TO SON 2017

Treatment	MAM	SON	Average
Maize Continuous-Fertilised (MCF)	4.16 a	2.80 a	3.48
Maize-Grazing (MG)	3.12 a	2.85 a	2.99
Maize-Continuous (MC)	2.99 b	2.73 a	2.85
Average	3.42	2.79	3.11

Note: Data within a column followed by different lower-case letters are significantly different ($P < 0.05$)

The results of this study were in agreement with the results of several studies showing that fertiliser application (inorganic) on maize can significantly increase yield. Maize yield and quality is greatly influenced by crop nutrition; maize is responsive to fertiliser especially nitrogen, phosphorus and potassium. Uwah et al. [18] observed that maize requires large amounts of soil nutrients to obtain a high yield . Application of NPK leads to a significant increase in crop biomass and grain yield [19]. Among the essential nutrients required by maize, nitrogen is the most commonly deficient nutrient in tropical soils [20]. Manure is a slow release fertiliser, which could explain the trend towards lower yield in MAM under maize grazing as compared to continuously fertilized maize [21].

The statistical difference of yield and biomass between the seasons may be attributed to erratic rainfall. Mugwe et al. [22] reported the effect of seasons on yield; drought stress occurs with different intensity in the plant development stage from germination to physiological maturity, while flowering is the most critical stage in maize. Management can also have an effect on the relative results of manures and fertilisers. Christensen et al. [23] attributed the significant difference between manure and fertilisers on cereal production at Askov to the time of application. During the years 1972 to 1992, fertilisers were applied in the spring but manure was applied in the autumn. The implication is that some of the manure N applied in autumn is lost, probably by leaching. This is evidenced by data of higher yields in the MAM than the SON season, while NPK fertiliser is applied at planting time; animals are left to graze over plots of land till the next rainy season starts.

Maize-grazing produced a higher grain yield compared to the maize-continuous. The higher yields from organic treatments could be due to positive effects of organic materials on the soil's physical and chemical properties [24], but the statistical difference between maize continuous-fertilised and maize-grazing indicates that organic manures provides a certain quantity of nutrients that are essential for plant growth and improving crop yields, but cannot be considered as full substitutes for inorganic fertilisers [25]. The concentrations of nutrients in maize in the maize-continuous fertilised, maize-continuous and maize-grazing is given in Table 4. Maize continuous-fertilised tended to have a relatively higher concentration of all the four nutrients (Ca, N, P and K), followed by maize-continuous for N, P and K. For N, maize-grazing rotation had a relatively higher concentration compared to maize-continuous. However, significant treatment effect was observed for only Ca ($P < 0.05$) with maize continuous-fertilised having a higher value compared to maize-grazing rotation and maize-continuous.

Cattle manure is an essential input for organic crop production, it is reported that the availability of N for plant uptake as part of the N supplied through organic inputs is immobile and not directly available for plant uptake [4, 26] thus the reason why MCF had more N compare to MG. Organic inputs, especially those with a high C/N ratio, may immobilize some of the N supplied through synthetic fertilisers. However, when immobilized N is mineralized over the course of the growing season. An improved synchrony between soil N availability and plant uptake may result in a higher N use efficiency of applied fertiliser [27] .

TABLE 4. AVERAGE NUTRIENT CONCENTRATION

Treatment	Nutrient concentration (g kg^{-1})			
	Ca	N	P	K
Maize Continuous-Fertilised (MCF)	18.2 a	13.2 a	8.3 a	13.2
Maize-Grazing (MG)	11.3 b	11.5 b	7.6 ab	11.9
Maize-Continuous (MC)	11.1 b	11.8 b	6.8 b	11.4
Average	13.3	12.1	7.5	12.1

Note: Data within a column followed by different lower-case letters are significantly different ($P < 0.05$)

3.2. Effect of Maize Cultivation-Cattle Rotation on Selected Physical and Chemical Properties of Ferralitic Soils in Uganda

The average effect of treatments on physical and chemical properties of two soil depths are shown in Tables 5 and 6. Compared to the initial soil pH which was acidic, bare ground (B) had the least decrease in soil pH while grazing-continous (GC) had the highest increase in pH. Maize continous fertilised (MCF), Maize continous (MC), and maize-grazing also experienced a decrease in soil pH; however all the treatments were within the pH critical value of 5.5–6.5 for optimum growth of many crops [28, 29]. Soil pH increment was only statistically significant in the GC treatment for both soil depths. Okigbo [30] reported that application of NPK fertiliser on soils that have experienced leaching can lead to deficiency of some nutrient elements, which may lead to soil acidification.

TABLE 5. AVERAGE EFFECT OF TREATMENTS ON PROPERTIES OF THE TOP SOIL (0-15 CM) OF SON 2015 TO SON 2017

Treatment[a]	pH	N	OM	Bray 1 P	Exch. Cations ($cmol_c$ kg^{-1})			
		(g kg^{-1})		(mg kg^{-1})	K	Ca	Mg	Na
B	5.5	1.6 c	28.0 b	6.34 b	0.41 b	0.97 b	4.21 a	1.35 a
GC	5.9	2.0 a	36.8 a	3.30 c	0.46 b	1.22 a	4.77 a	1.66 a
MCF	5.6	1.8 ab	26.8 b	10.64 a	0.67 a	0.93 b	4.53 a	1.53 a
MC	5.6	1.8 ab	26.7 b	4.08 c	0.43 b	0.85 b	4.62 a	1.74 a
MG	5.6	1.9 ab	26.8 b	4.79 c	0.44 b	0.87 b	4.77 a	1.62 a
Critical level	5.5–6.5	2.2	30	15	2–5	65–85	6–12	<1

Note: [a] B, Bare ground; GC, grazing continuous; MCF, maize continuous fertilized; MC, maize continuous; MG, maize-grazing; Data within a column followed by different lower-case letters are significantly different (P < 0.05)

TABLE 6. AVERAGE EFFECT OF TREATMENTS ON PROPERTIES OF THE SUB-SOIL (15–30 CM) OF SON 2015 TO SON 2017

Treatment	pH	N	OM	Bray 1 P	Exch. Cations ($cmol_c$ kg^{-1})			
		(g kg^{-1})		(mg kg^{-1})	K	Ca	Mg	Na
B	5.4	1.4 b	27.7 a	4.07 b	0.38 b	1.02 a	4.85 a	1.60 a
GC	5.5	1.5 b	23.9 a	3.19 b	0.33 b	1.14 a	4.23 a	1.46 a
MCF	5.7	2.0 a	23.5 a	8.63 a	0.65 a	1.13 a	4.66 a	1.57 a
MC	5.5	1.7 abc	22.9 a	2.21 b	0.35 b	0.70 b	4.82 a	1.69 a
MG	5.6	1.9 ac	24.4 a	2.74 b	0.46 b	0.97 a	4.79 a	1.72 a
Critical level	5.5–6.5	2.2	30	15	2–5	65–85	6–12	<1

Note: [a] B, Bare ground; GC, grazing continuous; MCF, maize continuous fertilized; MC, maize continuous; MG, maize-grazing; Data within a column followed by different lower-case letters are significantly different (P < 0.05)

The effect of cattle manure on increases in the soil organic matter pool that may lead to higher cation exchange capacity (CEC) and a higher soil pH [31, 32] thus enabling it to exert immediate and wider ranging beneficial effects on soil quality than inorganic fertilisers alone [33]. Treatment B had the least total N concentration effect followed by MCF, MC and MG, while GC had the highest treatment effect, although all the treatments were below the critical value indicating a deficiency in soil N after harvest. Nitrogen is one of the most important essential plant nutrients [34]. N in inorganic fertilisers is available for immediate plant consumption, thus explaining why MCF had the lowest N present after harvest, because the organic N in animal manures need to be mineralised to become available to plants. Grazing continuous had the highest increase in N compared to inorganic N fertilisers (MCF), which are quickly converted into soluble N forms, and are therefore susceptible to leaching, while organic inputs release nutrients more slowly and continuously throughout the growing season [35].

All Bray 1 P concentrations were below the critical value of 15 mg kg^{-1}. It is worthwhile to note that only the treatment MCF was near the critical value compared to the other treatments. The grazing-continuous treatment (GC) is the only treatment that had an average SOM above the critical value of 30 g kg^{-1}. Relative to inorganic fertilisers, soil organic matter content increased in the GC plot. This corroborates observations that manures contain significant amounts of organic matter and its application significantly increases soil organic matter more than NPK. Exchangeable potassium, calcium, and magnesium content in the soil remained generally below the critical levels for all treatments, as it was before the experimentation. However, potassium content was relatively high under MCF compared to the other treatments ($P < 0.05$). This is in line with observations of Gondek and Kopec [36] in both pot and plot experiments. Application of macro elements in mineral form usually affects their concentrations in plants to a greater degree than fertilization with these elements in the form of natural and organic fertilisers, mainly because the concentration of these elements in the latter is generally low [37]. In general, 90 to 100% of K in manure is available during the first year of application. For Ca all the treatments were below the critical value, and only GC soil had a Ca content nearer to the critical value. All the treatments did not show a significant difference in Mg and Na content for top and subsoils. However, compared to the baseline conditions significant increment were observed in all the treatments for Mg and Na.

4. CONCLUSION AND RECOMMENDATIONS

The maize grazing rotation reduces significantly the gap between fertilized and unfertilised maize on the ferralitic soils of central Uganda. In comparison with manure, potassium and calcium contents in maize biomass and soil significantly increased with inorganic fertiliser application. In light of the above results when access of NPK fertiliser is limited, we recommend the maize-grazing rotation to obtain a better maize yield on ferralitic soils. The practice is feasible and cost effective as the majority of households possess cows. However, there is a need to determine the minimum number of cows required for optimum yield and minimum land compaction. There is also a need to determine the nutrient supplement for attaining the optimum yield under different crops and grazing rotations.

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AGRONOMIC AND ENVIRONMENTAL EFFECTS OF SHIFTHING INTEGRATED CROPPING-LIVESTOCK SYSTEMS TO CONTINUOUS CROPPING ROTATIONS IN URUGUAY

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Abstract

Uruguayan agricultural rotations have been intensified and simplified. Continuous Cropping (CC) is replacing traditional Integrated Cropping-Livestock Systems (ICLS) with soybean (Glycine max L. Merr.) being the main crop. The objective of the three year term study (2014–2017) was to evaluate that shift in nitrogen (N) balance (NB) and nitrogen use efficiency (NUE) and its main components (recovery and internal efficiency) in a sequence of wheat-soybean using ICLS and CC under no tillage (NT) in Uruguay. Another aim was also to evaluate system of production is better matched with agronomic-economic and environmental sustainability principles. This study was carried out inside a long term experiment (LTE) established in 1993 on a Typic Argiudoll in Paysandú, Uruguay. The ICLS is characterized as a long rotation with 3½ years of crops and over the same period with pastures under open grazing. The CC system is a 3-year rotation using this crop sequence: wheat-soybean, barley-sorghum and fallow-soybean. Only wheat-soybean and pasture-wheat-soybean sequences were evaluated in CC and ICLS, respectively. Two experiments—non- isotopic and isotopic, one each in wheat and only isotopic in soybean—were established under both systems of rotation. The non-isotopic or conventional experiment was an N response experiment; it was established in plots of 10 m × 50 m. The treatments were four N rates (0, 30, 60 and 90 kg N ha-1) applied as urea and the N application was split (one half at planting and one half at tillering (Zadocks 2.2). The isotopic experiment was established to measure NUE in wheat and biological nitrogen fixation (BNF) in soybean. There was a wheat response to N fertiliser in both rotations. The yields were higher in CC, while the optimum N rate was always lower in ICLS. Although, this would indicate that there was a quantity of residual N derived from pastures, some growth factors other than N limited the attainable yields in ICLS. NUE and recovery efficiency (RE) were higher under ICLS. In contrast, internal efficiency (IE) was lower in ICLS, proving that factors other than N were limiting grain yield. The explanation could be that under such a rotation, which had a higher fresh C entry during the pasture phase led to a greater sequestration of nutrients in soil organic matter, such us N, and sulphur, among others. The results from isotopic experiments showed that the 15N recovery in plant was lower in ICLS than CC ($P < 0.05$), suggesting that 15N in that system was immobilized due to the presence of fresh C in order to sustain biological activity. The NB in the wheat phase was negative and similar between systems, whereas in the soybean phase it was positive, but higher in the CC system, because N input by BNF was higher in CC (72%) than in ICLS (64%). In the overall sequence, NB was similar in both systems (53 in CC and 56 kg N ha-1 in ICLS). Therefore, these results would indicate that, although NB was similar between systems, RE by crop productivity (N removed by grain) shows the lowest values under ICLS. On the other hand, the higher wheat yields were observed in CC, and also the highest N removed by grain that would

be compensated by a higher N input by BNF in soybean crops. However, the NUE by the wheat crop grown under this rotation was very low, implying a long-term higher risk of N losses. Such paradoxical results have been reported in other studies. This indicates that some ecosystems despite a low fertility (CC rotation) can still show high productivity, and by offering a way to maintain and improve soil fertility such as the ICLS rotation, the productivity does not improve.

1. INTRODUCTION

In Uruguay, integrated cropping-livestock systems (ICLS) may maintain a stable productivity for many years, based on the combined production of meat and agricultural products [1]. Work published in the 1990s, showed that the amount of N entering soil by BNF during the pasture phase fluctuates by 100 kg $ha^{-1}year^{-1}$, but could reach up to 240 kg ha^{-1} $year^{-1}$ [2]. This higher contribution of N improves following crops yields, leaving more residues in the soil and promoting C sequestration [3]. In Uruguay, organic C losses from 380 to 580 kg ha^{-1} $year^{-1}$ have been estimated in conventional tillage systems after 28 years of continuous cropping (CC) with grain crops fertilized and not fertilized with N and P, respectively. Another benefit, when legume-based pastures were included in those systems, soil organic matter (SOM) content tended to stabilize and organic C losses were reduced by 85 to 90% in relation to CC without fertilisers [4].

At the beginning of the 90s, no till (NT) technology was introduced in Uruguay, with the aim of reducing erosion and maintaining or increasing SOM [1, 5, and 6]. However, together with the advent of that technological change, ICLS began to be replaced by continuous cropping under NT with predominance of soybean crops into the rotation. As a consequence of this change, concern about the risk of generating negative N balances was raised [6, 8], which could lead to the need to raise N fertilization to maintain efficient plant N nutrition and high yields in the medium and long term resulting in negative effects on productivity and environmental sustainability. However, the magnitude of these effects could differ with the specific sequence of crops used (the nature of the preceding crop) and with the amounts of remaining residues (aerial and subterranean component), which are keys factors in the balance of N [9], C [10, 11], and P [12, 13]. One of the most widespread crop sequences in Uruguayan agriculture is the wheat-soybean succession. However, there is a lack of knowledge about the N balance in this succession and how much it can fluctuate with N inputs from BNF by soybean and with N outputs from wheat and soybean yields of its harvested products. The NB is also adjusted by the biological activity in the soil that accomplishes the role to synchronize the N on offer and plant demand.

A small but significant difference in the soil organic C (SOC) stock (0–0.18 m) of 3.6 Mg ha^{-1} ($P = 0.09$) in NT compared to conventional tillage (CT) was reported in a 12 year experiment [6]. According to these authors, such a difference could be explained by a diminishing of the C loss process (oxidation and erosion) in NT systems; due to the C input being similar in both systems. In that same experiment, on the other hand, the rotation effect by inclusion of perennial pastures did not affect the SOC stock, but a decrease in total N (TN) loss was evident. Those TN losses were observed in all systems evaluated, but they were 16% higher in systems that combined CC rotations and CT than ICLS rotations and NT management. In another work, comparing different ICLS treatments that differed in the time occupied with pastures (0, 30 and 50%) and different tillage systems (CT and NT), positive annual N balances

(NB) to neutral (only in the treatments with 50% of time assigned to the pasture phase) were reported [14]. In systems under CC or with 30% pasture, negative N balances of 36 and 16 kg ha^{-1} $year^{-1}$, respectively, were found [14].

The N contribution by BNF is essential to get the best balance between N inputs and N outputs in the current systems, because agricultural intensification has increased the N outputs from harvested products. Consequently, these agricultural systems are becoming increasingly dependent on N fertilisers use, which might lead to an increased environmental contamination risk [15]. In rotation systems that include legumes, the quantity of N fixed depends not only on intrinsic factors of each species, but also those associated with climate and agronomic management and the interactions between them. In this way, isotopic tracer technologies can be used in research to improve knowledge about N inputs and N outputs to the agricultural systems while increasing crop yields in a sustainable manner (i.e. conserving the natural resource base and protecting the environment) [16]. Keeping in mind the concept of sustainability, NUE by crops is an important parameter for evaluating agricultural production systems, because it can be significantly affected by factors such as fertiliser management practices [11, 13], tillage, and types of crops in the rotation.

The aim of this study was to evaluate the effect of two rotations: the ICLS, which was a traditional agricultural system in Uruguay ten years ago, and Continuous Cropping (CC), which replaced it. Soybean (*Glycine max* L. Merr.) is the main crop affecting NB and NUE in wheat-soybean rotations. The aim was also to determine which production system would be best matched with agronomic-economic and environmental-sustainability principles.

2. MATERIALS AND METHODS

2.1. Experimental Site

The study was developed inside a long term experiment (LTE) established in 1993 at the EEMAC Experimental Station, located near the city of Paysandú, Uruguay (32° 22' 41" S latitude and 58° 02' 50" W longitude). The site is under the influence of a humid subtropical climate (according to the Köppen climate classification) and it is fairly uniform nationwide since Uruguay is located entirely within the temperate zone. The average annual accumulated rainfall is 1300 mm, and the average temperatures in the winter and the summer are 12 and 24°C, respectively. The soil at the experimental area is classified as a Typic Argiudoll according to the USDA classification, with an A horizon of 18 cm with a pH 5.7, and clay, silt and sand of 289, 437 and 273 g kg^{-1}, respectively, and organic carbon (OC) of 29.5 g kg^{-1}, located on a slope of less than 1%.

The LTE is a combination of four soil use systems, set in main plots of 50 m × 50 m, and two tillage practices set in subplots of 50 m ×10 m, so that the size of each rotation-tillage plot was 10 m × 50 m arranged in a split-plot design with three or more replicates, depending on the crops in the rotation. However, for this study, there were just two soil use systems combined with one tillage system: only the Integrated Cropping-Livestock System (ICLS) and Continuous Cropping (CC) using No-Till was considered (Fig. 1). The reason for this choice is that they have been the most common rotations in Uruguay (Conventional tillage has almost completely disappeared as a tillage system). Also, in the LTE, several crop sequences (barley, sorghum, soybean and fallow) have been evaluated, but in this CRP Project only the wheat-soybean or pasture-wheat-soybean sequences were considered.

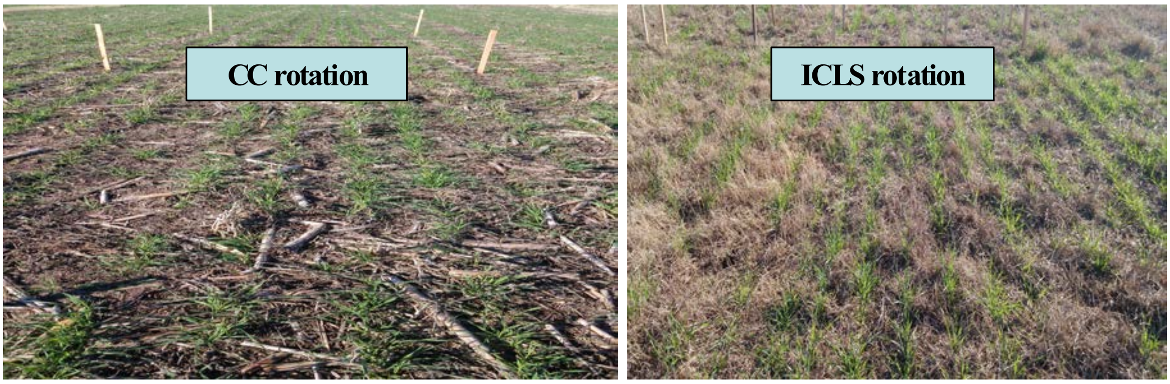

FIG. 1. Wheat crop at tillering (Zadocks 2.2) established in two systems: Continuous cropping (CC) and Integrated cropping Livestock system (ICLS) under no tillage (July 14th 2015).

The ICLS is characterized as a long rotation with 3½ years of crops and over the same period with pastures under open grazing. The pasture is a mixture of birdsfoot trefoil (*Lotus corniculatus* L.), white clover (*Trifolium repens* L.), and tall fescue (*Festuca arundinacea* L.), grazed by dairy cattle at a stocking rate of 60 cows ha^{-1}, with a variable frequency depending on the forage dry matter availability.

The grain crops in ICLS, consist of a succession of wheat (*Triticum. aestivum* L.) and barley (*Hordeum vulgare* L.) as winter cover crops, or fallow if the previous crop was sorghum (*Sorghum bicolor* L.), and soybean (*Glycine max* L.) and sorghum as summer crops. Soybean could be defined as a first or second crop and it depends on the purpose of the previous crop: i.e. if it was cultivated for grain harvest, soybean is defined as a second crop, but if there was a fallow or a crop not harvested, it is classed as a first crop. The CC system is performed with the same grain crop sequences as in ICLS (Table 1).

TABLE 1. SYSTEMS AND CROPS PHASES EVALUATED DURING THE PERIOD UNDER STUDY (2014–2017)

	7-year rotation						
Rotation	1	2	3	4	5	6	7
ICLS	Wheat/ Soybean 1	Barley/ Sorghum	Fallow/ Soybean 2	Wheat + P1	P*2	P3	P4

**P= Pasture*

	3-year rotation			3-year rotation			
Rotation	1	2	3	1	2	3	**1**

CC	Wheat/ Soybean 1	Barley/ Sorghum	Fallow/ Soybean 2	Wheat/ Soybean 1	Barley/ Sorghum	Fallow/ Soybean 2	Wheat/ Soybean 1

Note: The ellipses enclose the phases of crops and pasture that were evaluated in this study

The pasture in ICLS was installed toghether with the winter crop (wheat) in the same planting operation. Also, for this system, glyphosate herbicide was applied in plots with 3½ year pastures (P4) plots, before planting wheat. In this work, only wheat and soybean crops were evaluated (Table 1).

2.2. Experiments and Experimental Design

Experiments were carried out in two crop rotations: 1-ICLS and 2-CC using no-tillage in the two crop phases (wheat and soybean). The wheat crop evaluated under ICLS was planted after a pasture with 3½ years of age, whereas in CC after soybean (in this case the first crop). Two experiments (conventional or non-isotopic and isotopic) were established; one each in wheat and only isotopic in soybean.

2.2.1. Conventional N response experiment (wheat)

The objective of this experiment was to evaluate the rotation effect (ICLS vs CC) on wheat grain yield, the optimum N rate to maximize grain yield, NB and NUE and its main components. Treatments were four N rates (0, 30, 60 and 90 kg N ha^{-1}) applied as urea and the N application was split, one half at planting and another one at tillering (Zadocks 2.2). The experiment was established in plots of 10 m × 50 m and the treatments were arranged in a randomized complete block design with 3 replicates. This experiment was performed completely in 2015 and 2016, because in 2014 just two N rates (0 and 30 kg N ha^{-1}) could be established. At planting and over the entire experimental area, phosphorus was broadcast without incorporation at 60 kg ha^{-1} as triple superphosphate.

At physiological maturity, sampling of plants were made from 1 m of row for biomass determination. Each plant sample was separated into grain and straw to determine dry matter yield, N concentrations and their ratios. At crop harvest, grain yield was determined at each system (ICLS and CC) and was performed in all years of the study (2014–2016). For grain yield, the harvest area of each plot was 1.15 m × 4 m. The grain was weighed and the moisture content was determined in order to correct the wheat yield by using a base moisture level of 13.5%.

With the data from conventional plots, NUE and its main components were estimated: *N recovery efficiency (RE)* and *internal efficiency (IE)*. Nitrogen use efficiency is also called agronomic efficiency and it was determined by the following equation:

$$NUE(kg\ grain\ kg\ N^{-1}) = \frac{Grain\ yield_{Fert} - Grain\ yield_{UnFert}}{Napplied} \quad (1)$$

where, grain yield$_{Fert}$ and grain yield$_{UnFert}$ are grain yields at a certain level of N applied and in the control treatment, respectively.

The RE is the total amount of N absorbed in fertilized and unfertilized N plots per kg of applied N. This ecophysiological parameter, is defined by the equation:

$$RE(kg\ Nuptake\ kg\ N^{-1}) = \frac{N\ uptake_{Fert} - N\ uptake_{UnFert}}{Napplied} \qquad (2)$$

where N $uptake_{Fert}$ and N $uptake_{UnFert}$ are total plant N uptake (kg ha^{-1}) in the aboveground biomass at a certain level of N applied and, in the control, respectively.

The IE is the total grain yield produced per unit of N absorbed. This physiological parameter is also called physiological efficiency (PE) and is defined as:

$$IE(kg\ grain\ kg\ Nuptake^{-1}) = \frac{Grain\ yield_{Fert} - Grain\ yield_{UnFert}}{N\ uptake_{Fert} - N\ uptake_{UnFert}} \qquad (3)$$

These parameters are interrelated.

$$NUE(kg\ grain\ kgN^{-1}) = RE \times IE \qquad (4)$$

Finally, we also estimate another term used to provide information about the relative utilization of N fertiliser applied in crop production [17], which was named in this work: recovery efficiency according to crop productivity (RE_{CP}). It can be expressed as the ratio between the amount of fertiliser N removed with the crop (the difference between N grain removed by fertilized crops (N grain $removed._{Fert}$) less N grain removed by unfertilized crops (N grain $removed._{UnFert}$) and the amount of fertiliser N applied. This agro-environmental parameter is defined by the equation:

$$RE_{CP}(\%) = \frac{N\ removed_{Fert} - N\ uptake_{UnFert}}{Napplied} * 100 \qquad (5)$$

2.2.2. Isotopic experiment (wheat)

The objective of this experiment was to measure NUE in wheat and to evaluate the rotation system effect and timing of N application on the ^{15}N recovery in soil and crop as well as on the ^{15}N balance. Treatments consisted of three N rates (0, 30, and 60 kg N ha^{-1}) applied to micro plots of 1 m × 1 m as enriched urea with 5 atom % ^{15}N excess and applied at one or at the two selected timings; planting and Zadocks 2.2 (Table 2). In this way, it was possible to study the NUE of each N timing independently, and with no interaction of the N rate. Nitrogen rate treatments were arranged in a randomized complete block design with 3 replications.

TABLE 2. N RATES (KG/HA) APPLIED AT PLANTING AND TILLERING (ZADOCKS 2.2) IN THE ISOTOPIC EXPERIMENT

Planting	Tillering	Total N rate
0	0	0
30*	0	30
0	30*	30
30*	30	60
30	30*	60

Note: * denotes ^{15}N-labeled urea (5 atom % ^{15}N excess) applied

In this experiment, the harvest area of microplots was 0.34 m^2. Following the same procedure as the conventional experiment, each plant sample was separated into grain and straw in order to analize them separately. After wheat harvest, a soil sampling was carried out in the microplots, which had been labeled with ^{15}N. From each microplot, two sample cores were obtained at each sampling point, and the sampling was performed at layers of: 0–5, 5–10, 10–20 and 20–40 cm. The surface layer (0–5 cm) was made with a tool with greater diameter than the one used for the deeper depths. In this way, it was possible to clean the sampling hole of the first layer and insert a pipe to prevent ^{15}N contamination between superficial and deeper samples. Soil samples were taken in 2014 and 2016, but in the CC rotation sampling could be done just until 15 cm of depth, whereas in ICLS it was possible to sample until 45 cm of depth.

With the data from isotopic plots the ^{15}N recovery in plant and soil was estimated. First, the proportion of N derived from fertiliser (NdfF) was estimated in plant (straw or grain) and soil, by applying Equation 6 and Equation 7, respectively, which are detailed below.

$$NdfF_{plant}(\%) = \frac{at.\%^{15}Nexc.plant}{at.\%^{15}Nexc.fertilizer} \qquad (6)$$

$$NdfF_{soil}(\%) = \frac{at.\%^{15}Nexc.soil_{(depth.x)}}{at\%^{15}Nexc.fertilizer} \qquad (7)$$

The $NdfF_{plant}$ values were expressed as kg N ha^{-1} by multiplying that N fraction by the crop N yield (crop biomass at physiological maturity). The quantity of N in the wheat grain derived from the fertiliser was also estimated. The estimation of N use efficiency (NUE) or fertiliser use efficiency (FUE) was calculated with equation 3. Efficiency per component (straw and grain) was calculated with Equation 8.

$$NUE(\%) = \frac{NdfF\ (kgha^{-1})}{N\,Rate(kgha^{-1})} \qquad (8)$$

The quantity of ^{15}N recovery in soil (at each depth and in the whole sampling depth) was also expressed as kg N ha^{-1}.

2.2.3. Estimation of N balance in the wheat phase

Knowing the recovery data in plant and soil, the ^{15}N balance was estimated by assuming that the N not accounted for was associated with N losses from the system. In order to know the overall N balance (NB), the quantity of N derived from soil exported with harvested products (the difference between N yield grain and $NdfF_{grain}$) and also the quantity of N losses from soil (which was assumed as 20% of N losses from N fertiliser) were estimated. The difference between NB from soil and NB from ^{15}N fertiliser estimated the overall NB in the wheat phase. This NB estimate was made from data of the wheat crop fertilized with 30 units of N.

2.2.4. Conventional and isotopic experiments (soybean)

The objective of this experiment was to measure the grain yield and BNF in soybean and to evaluate the rotation system effect on the partial soil N balance. After each wheat harvest, soybean was planted in both rotations (ICLS and CC), within the same 10 m × 50 m plots used in the wheat experiment, but in a different area, which never received ^{15}N-fertiliser. In this way, the ^{15}N variability caused by the previous isotopic experiment was avoided.

Sorghum was also planted in ICLS and CC systems, alongside and close to the soybean plots, and was used as the non-fixing crop reference for BNF estimation. BNF was estimated with the ^{15}N natural abundance (NA) method and the isotopic dilution (ID) technique. Using the ID method, at plant emergence, both crops were fertilized with ammonium nitrate at a rate of 10 kg N ha^{-1} enriched with 10-atom % ^{15}N excess. The labelled fertiliser was applied only to micro plots of 1 m × 1 m to asses BNF.

At the R5.5 stage of soybean, the whole aerial part was harvested, and the pods were separated from the rest of the plant components, and were later analysed separately. In the case of sorghum, a similar approach was used with the grain. The plant samples were collected from the centre of the labelled micro plots (0.25 m^2) for BNF estimation by the ID method. Another set of soybean and sorghum plants were collected from a larger non-labelled area (1 m row) for BNF estimation by the NA method [18].

To estimate BNF-NA the following equation was used:

$$BNF - NA = \frac{\delta^{15}N_{ref} - \delta^{15}N_{fiix}}{\delta^{15}N_{ref} - B} \qquad (9)$$

Where:

- $\delta^{15}N_{ref}$ represents the isotopic value of the non-N_2-fixing plant used as a reference growing under similar condition as the fixing plant,
- $\delta^{15}N_{fix}$ is the isotopic value of the fixing plant and,

- B is the $\delta^{15}N$ value of the fixing plant when it obtains its N entirely from atmospheric N_2.

On the other hand, the ID technique assumes that the isotopic effects are negligible and B approaches zero when ^{15}N levels are higher than the ^{15}N background level [19]. The proportion of legume N derived from atmospheric N_2 was then calculated for the ID technique as follows:

$$BNF - ID = 1 - \frac{at\%^{15} N_{fiix}}{at\%^{15} N_{ref}} \tag{10}$$

The isotopic concentrations of fixing and reference plants were expressed as atom % ^{15}N excess. Another plant sampling was made at physiological and commercial maturity to estimate grain and straw yield of soybean by harvesting 3 rows × 1 m (0.45 m row width) from a non-^{15}N labeled area. In the soybean crop planted in 2014 the grain could not be harvested due to logistical problems.

2.2.5. Estimation of N balance in the soybean phase

The difference between aboveground N fixed and N exported by soybean grain harvest is the estimate of NB. The proportion of N fixed was estimated at the R.5.5 stage and the total biomass was determined at around the time of peak biomass (physiological maturity, before leaf fall). In view of the fact that N inputs other than BNF (e.g. atmospheric deposition) were not taken into account, as well as outputs other than N exported by soybean grain, such as N losses by denitrification or leaching, NB could only be regarded as a partial estimate. In addition, the amounts of N fixed for soybean was estimated using two ways: based on the aboveground biomass and on the above- + below-ground N (N associated with roots, nodules and rhizo-deposits), although the latter N input was not directly measured. To estimate such an N input, a single root correction factor was used to convert above-ground biomass into whole plant N [20]. The correction factor used for soybean was 1.61 [20].

2.2.6. N inputs in the pasture phase

Pasture yield was determined after a grazing event by harvesting a 6 m × 3 m area. Plant samples obtained from each cut were separated into the three species of interest (lotus, clover and tall fescue) and the rest was grouped as weeds. The NA technique was also used in pastures in order to estimate the BNF of birdsfoot trefoil and white clover species that were present in mixed swards. The reference used for that estimation was tall fescue plants that were growing in the mixture with legumes in the ICLS rotation. N outputs were not estimated in this phase, but according to published reports it would be minor because the majority of N would be recycled from urine and excreta by cattle grazing.

2.3. Data Collected and Analyses

2.3.1 Weather data (2014–2017)

The cumulative precipitation during the wheat growing season (from June to November) was higher in 2014 with 965 mm, whereas in 2015 and 2016 the rainfall was 892 and 635 mm, respectively. During the soybean growing season (from December to May), the cumulative precipitation was very low in 2014–2015 at 586 mm, whereas in the next years, 2015–2016 and 2016–2017 it was 2.5 and 1.5 times higher than in the first year.

In all years, the average monthly temperature was highest in January and lowest in June, except in 2015 when the lowest was in July. There was also a negative relationship among seasons and temperatures, because the higher January mean temperature had the lowest June mean temperature, while the contrary was also observed. The monthly average temperature and cumulative monthly precipitation during the study period (2014–2017) are shown in Fig. 2. Weather data was supplied by a local meteorological station at the EEMAC Experimental Station.

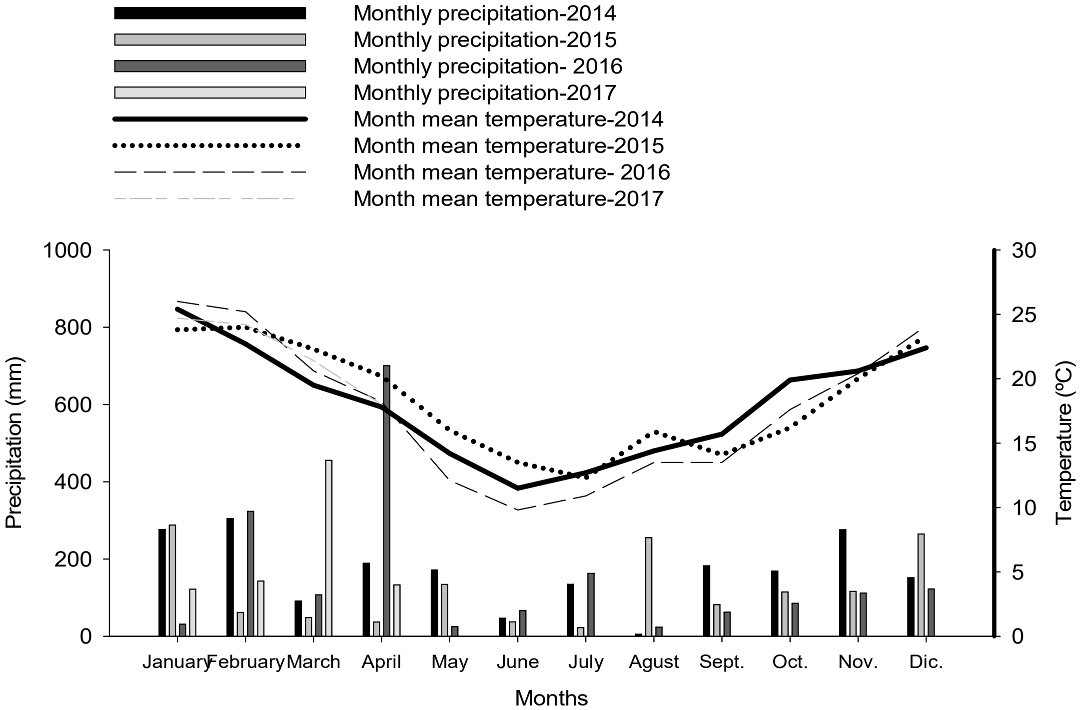

FIG. 2. Weather data from 2014 to 2017 in Paysandú, Uruguay (data supplied by EEMAC Experimental Station).

2.3.2 Soil and plant analysis (2014–2017)

Soil samples from the conventional experiments (in wheat and soybean phases) were randomly collected at the 0–20 cm layer within each experimental plot (over three years). These soils samples were obtained for measurement of mineral N content, nitrate (NO_3^--N) and ammonium (NH_4^+-N) at sowing in soybean (Table 3) and wheat and at tillering (Z 2.2) in this last crop (Table 4). The N-NO_3^- concentration at 0–20 cm of soil depth used in this study is the parameter that has been used for the N diagnostic for Uruguay's wheat crops.

Nitrate-N concentration tended to be higher in CC than ICLS rotations in the wheat phase. In all years it was also greater at planting than at tillering (except in 2015) which on average corresponded to ~ 20 vs. 40 kg N ha^{-1}, respectively. In contrast, in the soybean phase the NO_3^- -N content was higher, in both years (2015 and 2016) under ICLS than the CC system (Table 3).

TABLE 3. NITRATE CONCENTRATION IN SOIL AT PLANTING IN SOYBEAN GROWING IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) IN 2015 AND 2016

Rotation	Nitrate-N at planting (mg kg^{-1})	
	2015	2016
CP	23.0 a	24.9 b
CC	19.5 a	19.3 a
CV (%)	20.6	3.0

Note: Means with a common letter are not significantly different (p> 0.05)

TABLE 4. NITRATE CONCENTRATION IN SOIL AT PLANTING AND TILLERING IN WHEAT GROWING IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) AT TWO N RATES (0 AND 30 KG HA^{-1}) DURING 2014-2015

Rotation	Nitrate-N (mg kg^{-1}) at					
	Planting	Tillering	Planting	Tillering	Planting	Tillering
	2014		2015		2016	
ICLS	11.6 a	4.8 a	7.0 a	15.5 a	10.2 a	4.4 a
CC	11.1 a	3.3 a	10.6 a	17.3 a	13.1 b	6.2 b
CV (%)	36	27	34	26	6	16

Note: Means with a common letter are not significantly different (Tukey's test, *P* ≤ 0.05) and are average values of the two N treatments (0 and 30 kg N ha^{-1})

Soil samples from isotopic experiments carried out in wheat were processed in the lab in another way. At each soil sampling, a soil sub-sample was obtained and recorded the volume and dry weight (to 105 ºC) to estimate the N mass equivalent and to express data to kg N ha^{-1}. All soil samples were oven dried at 40 ºC for 48 h until the mass remained constant, whereas plant samples were oven dried at 65 ºC for 48 h until the mass remained constant. Then, soil and dried plant materials were grounded in a rotary mill (SampleTek Model 200 Vial Rotator, Lincoln, Nebraska) to a fine powder (typically a consistency approaching to that of the talcum powder), which was necessary for isotopic analysis by mass spectrometry.

Total N (TN) concentration (Dumas method; IAEA, 1990) and $^{15}N/^{14}N$ ratios for the soil and plant samples (both at ^{15}N natural abundance and enriched levels) were determined using an elemental analyser (Flash EA 112) coupled to an isotope ratio mass spectrometer (DeltaPLUS, Finnigan MAT, Bremen, Germany). The standard deviation of repeated measurements of a laboratory standard (leucine) was 0.1% and 0.3‰ for TN and $\delta^{15}N$ respectively. All N and ^{15}N analyses reported in this study were done with the equipment

(IRMS) in the facilities available in the CATNAS Laboratory located at the Soil and Water Department, FAGRO, UdelaR (http://www.fagro.edu.uy/catnas).

2.3.4 Statistical analysis

Analysis of Variance (ANOVA) was performed for aerial biomass yield (crops and pastures), grain yield (wheat and soybean crops), total N in aerial biomass (crops and pastures), fixed N biomass (soybean and forage legumes), and N grain yield (crops), and ^{15}N recovery in soil and plant in the wheat phase using Info Stat version 2008. Mean yields of treatments were separated using the least significant difference (LSD) test at the 5% level, and for the other means the Tuckey's test at the 5 or 10% levels of significance. All values are reported as means of three replicates.

3. RESULTS AND DISCUSSION

3.1. WHEAT PHASE

3.1.1. Productivity, optimum N rate and FUE and its main components derived from wheat N response experiments

Wheat grain yield was statistically ($P \leq 0.05$) higher in CC than ICLS (Table 5 and Fig. 3), in almost all N treatments ($LSD_{0.05}$> 360 in 30N and $LSD_{0.05}$> 620 kg ha^{-1} in 90N), except for 60N where there was no difference. The significant difference for grain yield between rotations, was also observed in the control treatment ($LSD_{0.05}$ > 368 kg ha^{-1}) and it was consistent in the 3 year study. However, N uptake at physiological maturity and N grain yield at harvest followed a similar trend observed for grain yield, with CC achieving the highest values, but such difference was statistically significant only in 30 and 90 N rates (Table 5).

It is important to note that in 2015 the germination of wheat was poor in the ICLS rotation (Fig. 1), which obviously affected the final plant stand establishment and consequently the grain yield and other parameters related with NUE of the crop growing in the system. For the CC system, N uptake increased linearly in response to N addition up to the maximum N rate, i.e. 90N, but for ICLS the relationships between N uptake and N fertiliser rate fit a quadratic model. The trend in ICLS suggests no further increase in N uptake above 60N (Fig. 4c). The slope of these relationships i.e. RE was significantly different as a result of the rotation effect (Fig. 4c). The crop N recovery of N fertiliser per unit of N added was 64% in the CC rotation, whereas in ICLS the RE was more than 100% (Fig. 4c). Consistently with that observed in RE (Fig. 4c), grain yield showed the same trend with higher increments in response to N applied to wheat growing under ICLS than under CC (Fig. 4a). Therefore, NUE for N fertiliser rates between 30 and 90 kg ha^{-1} were ca. 20 and 97 kg grain kg^{-1} N for CC and ICLS, respectively (Fig. 4a). Then, NUE i.e. kg grain kg^{-1} N was almost 5 times higher for wheat grown under ICLS than under the CC rotation (Fig. 4a).

TABLE 5. GRAIN YIELD, N UPTAKE AT PHYSIOLOGICAL MATURITY AND GRAIN N YIELD OF WHEAT IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) AT FOUR N RATES

N rate ($kg\ ha^{-1}$)	Rotation	N uptake	Grain yield	N grain yield
		($kg\ ha^{-1}$)		
0	CC	29	1467	25
	ICLS	32	1086	21
	$LSD_{0.05}$	ns	336	ns
30	CC	38	2072	36
	ICLS	48	1541	28
	$LSD_{0.05}$	9	361	6
60	CC	60	2651	45
	ICLS	61	2417	42
	$LSD_{0.05}$	ns	ns	ns
90	CC	54	3198	59
	ICLS	85	2236	40
	$LSD_{0.05}$	17	620	11

Note: Rotation and N rate effects were significant at $P \leq 0.001$ as a source of variation on all variables, but the rotation*N rate interaction effect was just significant ($P \leq 0.0033$) on N yield. In 0 and 30N the values are means of three replicates* three years (2014–2016), whereas 60N and 90N are means of three replicates* two years (2015–2016).

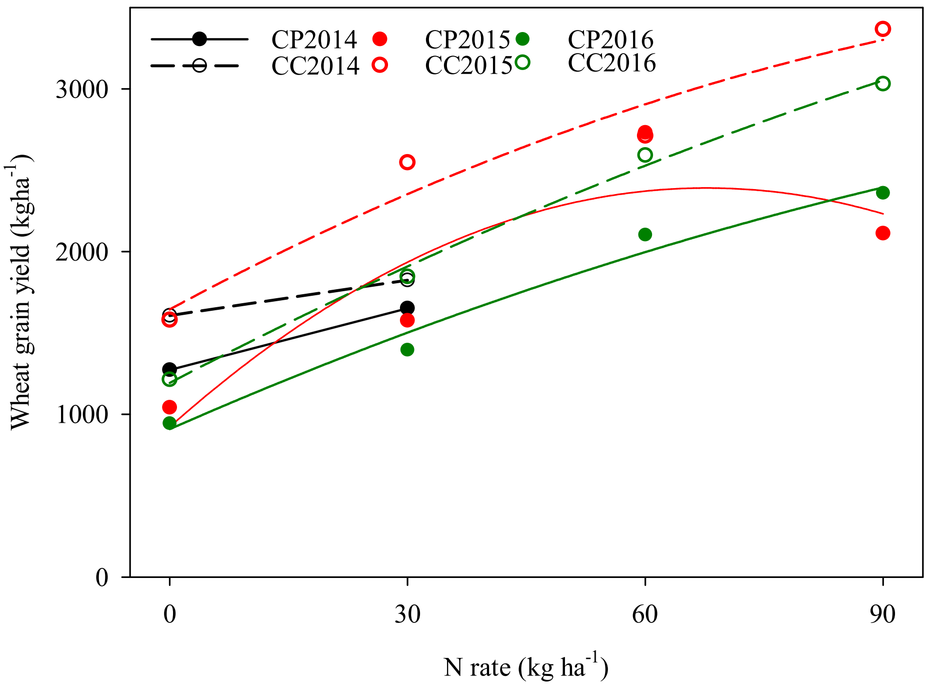

FIG. 3. Relationships between grain yield and N fertiliser rate of wheat growing under two rotation systems (CC and ICLS) in 2014, 2015 and 2016. Solid and dashed lines represent the linear regression for ICLS and CC, respectively.

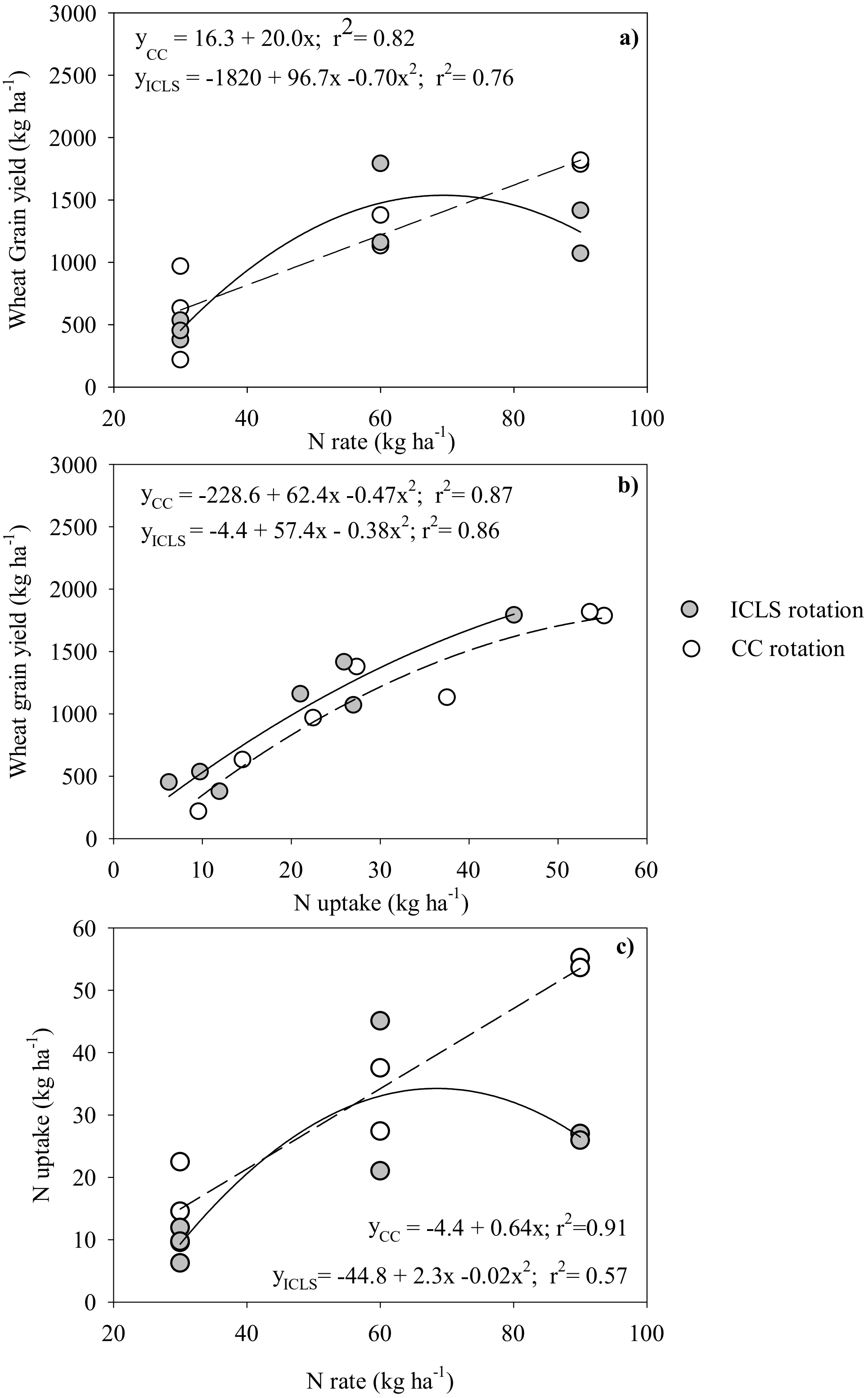

FIG. 4. Relationships between (a) grain yield and N fertiliser rate (b) grain yield and N uptake at physiological maturity and (c) N uptake at physiological maturity and N fertiliser rate of wheat growing under two rotation systems (CC and ICLS). Solid and dashed lines represent the linear regression for ICLS and CC, respectively.

The relationships between nitrogen uptake at physiological maturity and grain yield fit a quadratic model in both systems. The slope of these models (i.e. IE) was significantly affected by rotations (Fig. 4b), so a particular internal efficiency was found for each rotation (i.e. 57.4 and 62.4 kg grain kg^{-1} of N uptake for ICLS and CC, respectively). Furthermore, NUE was higher in ICLS due to its higher RE, which may be explained by a low soil N availability, revealed for the lowest wheat grain yield in the control treatment (0N), and this was consistently observed in the 3 year study. This result could also be associated with the lower mineral N content (nitrate-N + ammonium-N) that was found at planting as well as at tillering of wheat (Table 4). This result suggests that soil N availability was an important factor limiting the current wheat yield in that system.

Nevertheless, factors other than N may certainly be limiting the yield in ICLS. These factors could not be determined in this study but it might be revealed from the lowest IE. It represents the ability of a plant to convert a given amount of fertiliser N into grain yield. In our case, the low IE would suggest more suboptimal or worse growth conditions in ICLS than CC, maybe caused by factors such as nutrient deficiencies other than N or the presence of weeds. In this sense, it is important to point out that the experimental area was fertilized with phosphorus, but not with potassium and sulphur that are also essential nutrients for a good wheat yield. Therefore, low IE could be explained by one or more nutrient deficiencies, which we presume could mainly be sulphur, because it has been reported to have a great effect in either of the two parameters of NUE in wheat [21]. The lower N availability under ICLS could be the result of higher N immobilization, and this biological process could also be affected by other nutrients such as sulphur or phosphorus.

The RE_{CP} estimated by Equation 5 (Table 6) values would suggest that the relative utilization of N fertiliser applied in crop production was almost three times lower in ICLS than CC systems (27 vs. 74%, respectively). In the CC system, at low N application rates the N removal in wheat grain exceeded the N input, i.e. RE_{CP} was higher than 100% (Table 6). This situation can be described as “soil mining,” and as a consequence yields are declining. At higher application rates in such systems, substantially decreasing RE_{CP} implies increased risk of N losses. In the ICLS system, RE_{CP} was always low and similar among N rates. These results reveal that the highest RE observed in this system (Fig. 4c) was weakly related with RE_{CP}, whereas with CC it was more closely related (Fig. 5), suggesting that N fertiliser that was absorbed by the crop (ca. 68%) is removed in grain, whereas in ICLS it was too low and also not related with the proportion of N uptake by the crop. Such results would explain the lower IE observed in the ICLS rotation (Fig. 4c). For example, the wheat crop had high efficiency to uptake N from the N added as fertiliser but a very low proportion of it was removed in grain.

3.1.2. Main outputs from the conventional experiment

The wheat crop performance was greater under CC than the ICLS rotation, which was consistently observed in all years of this study. Nevertheless, it is important to indicate that the NUE was higher under ICLS, maybe due to a better synchronization between N plant demand and N supplied by the soil and the fertiliser added. Subsequently, the lowest grain yield obtained in ICLS may be caused by nutrient deficiencies other than N, possibly more associated with nutrients cycling coupled to SOC.

TABLE 6. RE_{CP} OF N FERTILISER APPLICATION IN WHEAT GROWN UNDER CC AND ICLS ROTATIONS

Rotation	N rate	N removed	RE_{CP}
	kg ha^{-1}		(%)
	30	36	121
	60	35	59
CC	90	39	43
	Mean	37 b	74 b
	30	7	23
ICLS	60	22	37
	90	20	22
	Mean	16 a	27 a

Note: significant rotation effects in ANOVA at *P* ≤ 0.1. In 0 and 30N the values are means of three replicates * three years (2014–2016), whereas 60N and 90N are means of three replicates* two years (2015–2016).

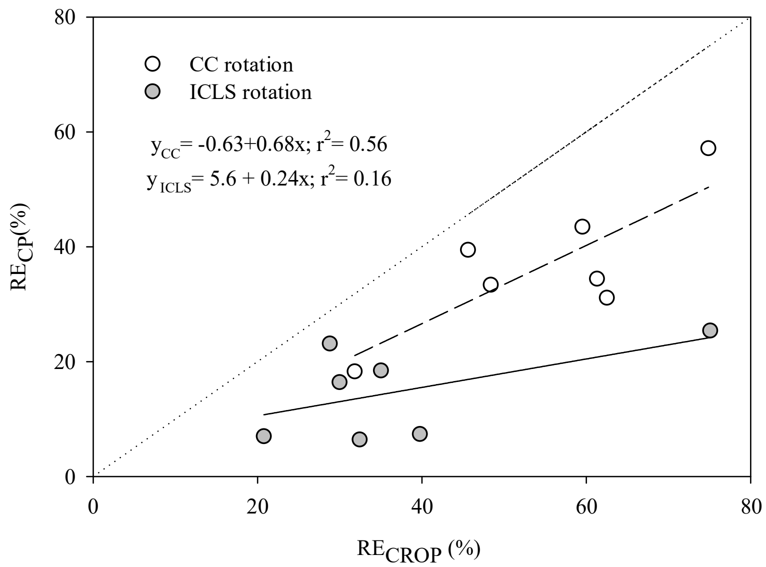

FIG. 5. Relationships between recovery efficiency (RE) and crop productivity (RE_{CP}) by rotation. RE values are means of 3 replicates per N rate applied to wheat grown under CC and ICLS rotations during the period 2014–2016. The dotted 1:1 line represents values for which all crop N uptake from fertiliser would be expected to be exported in wheat grain.

3.1.3. *Effect of systems rotation on ^{15}N recovery, recycled N, and N losses*

The results from isotopic experiments showed that the average ^{15}N recovery (from 2014–2016) in crops at physiological maturity was statistically different between systems, 25 vs. 35 % in ICLS and CC, respectively (Fig. 6 and Table 7). Such differences appear to be the result of N "pool substitution." This phenomenon results in an ^{15}N dilution of plant available N because ^{15}N fertiliser would be immobilized in the microbial biomass while unlabeled N from the native N pool is mineralized [22]. In ICLS, the ^{15}N immobilization would be more pronounced than in CC, because under that rotation large amounts of labile C substrates were supplied via organic residues during the pasture phase. Consistently with this, the proportion of N derived from fertiliser remaining in the soil after wheat harvest, tended to be higher in ICLS (39 and 33 %) than in CC (30 and 29 %) for 2014 and 2016, respectively (Table 7). However, these results in ^{15}N recovery in soil were not statistically different between systems.

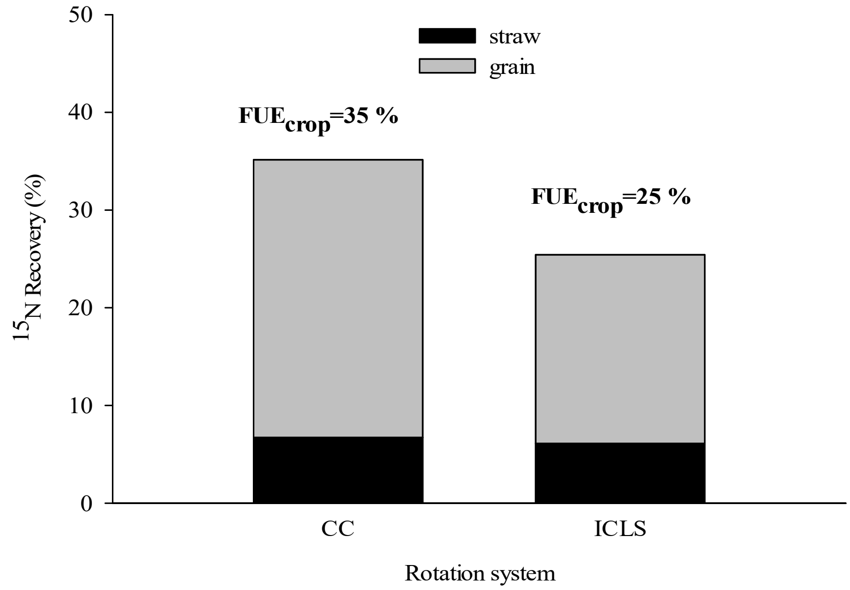

FIG. 6. ^{15}N recovery at physiological maturity in wheat (aerial components) in ICLS and CC rotations. Note: The data set was derived from isotopic experiments set up in the three-year study (2014–2016), applying 30 kg N ha^{-1} with a labeled N fertiliser at tillering.

TABLE 7. AVERAGE ^{15}N RECOVERY IN CROP AND SOIL, ^{15}N RECYCLED AND N LOSSES DURING THE WHEAT PHASE IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) IN 2014–2016

System	Year	Recovery ^{15}N (%)				N recycled*	N loss (%)
		Grain	Straw	Crop	Soil	(%)	
CC	2014	17 a	7 a	24 ab	30	37	45
	2015	34 b	7 a	40 bc			
	2016	34 b	7 a	41 c	29	36	30
	Mean	28 B	6A	35 B	30 A	37 A	38 A
ICLS	2014	17 a	9 a	26 ab	39	48	35
	2015	17 a	5 a	21 a			
	2016	24 ab	5 a	29 abc	33	38	38
	Mean	19 A	6A	25 A	36 A	43 A	37 A

Note: means followed by the same lowercase letter within a column are not significantly different among system*year and means followed by the same capital letter column are not significantly different among systems (Tukey test, $P > 0.05$).

3.1.4. Effect of application timing of N on ^{15}N recovery and N losses

Data analyses of this section were derived from the isotopic experiment set up in 2016, where treatments consisted of different N application timing. Only in this year was it possible to perform different N treatments combining two timing applications with two N rates, and also to get complete information about ^{15}N recovery in the main components of the system (crop and soil). The ^{15}N recovery in the first 5 cm of the soil profile was higher than deeper soil layers in all N treatments and rotations (Figs. 7 and 8). This could be explained by the higher amount of SOC (data not shown) in the surface soil. Taking into consideration just the first 15 cm of the soil profile for ANOVA, the amount of N derived from fertiliser was affected by the N application timing (P = 0.0056), but such an effect was also significant in interaction with rotation (P=0.048) and soil depth (P=0.0373). The first interaction showed that ^{15}N recovery in soil was highest at tillering in both rotations, but in the CC rotation it was different between N application timings (1.24 kg ha^{-1} at planting vs. 2.32 kg ha^{-1} at tillering), whereas in ICLS rotation it was similar (1.68 kg ha^{-1} at planting vs. 1.87 kg ha^{-1} at tillering). The interaction between N application timing* and soil depth shows that ^{15}N recovery in soil was lower at planting than at tillering (2.82 vs. 4.27 kg ha^{-1}, respectively), whereas in the other soil depths it was similar for both N application timings.

Nitrogen application timing also had a significant effect on ^{15}N recovery by crop and ^{15}N not accounted for, and this last variable was associated with N losses from the system (Fig. 9). In both N treatments (30*–0 and 30*–30), when N was applied at planting ^{15}N recovery in crop (grain + straw) was almost three times lower than when N was applied at tillering (12 vs. 35%, respectively). In consequence, N losses were about twice as great when the N fertiliser was applied at planting than at tillering (21 and 12%, respectively).

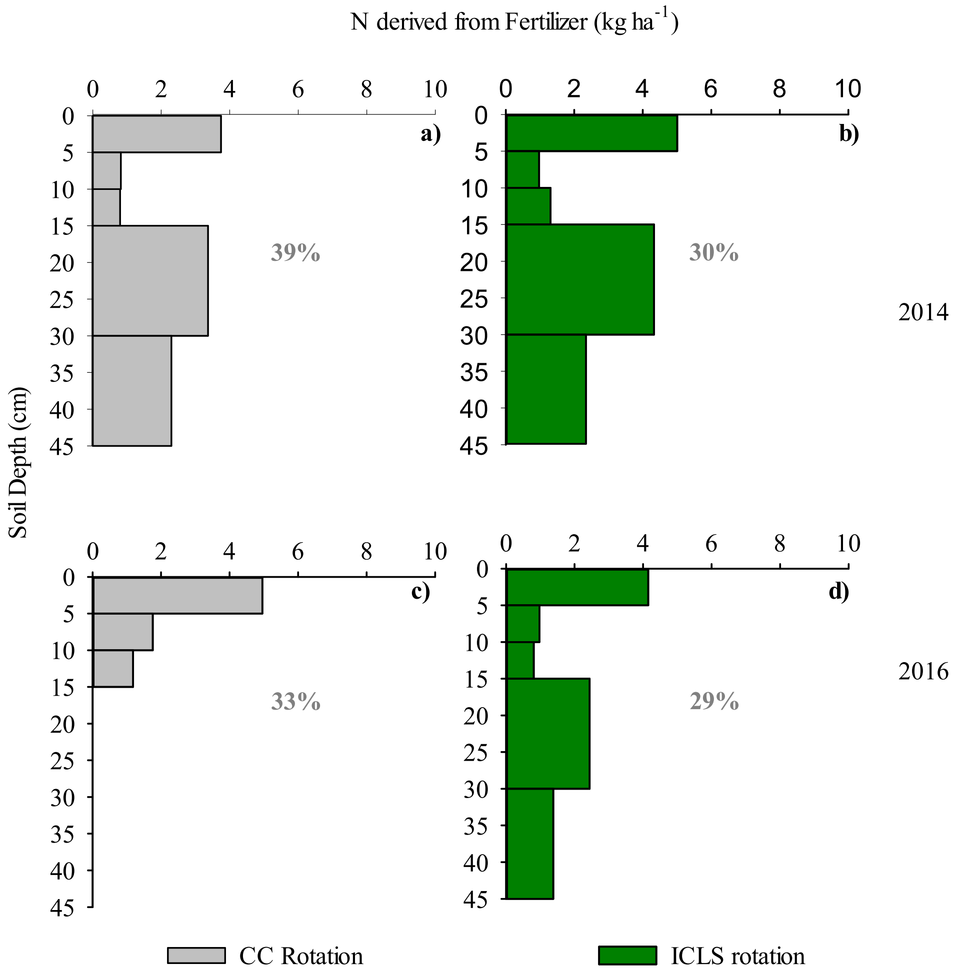

FIG. 7. Distribution of N derived from fertiliser (kg ha^{-1}) at harvest at different soil sampling depths. The total ^{15}N recovery (in %) in the soil profile is indicated for CC (a and c panels) and ICLS (b and d panels) from the data set obtained in 2014 (a and b panels) and 2016 (c and d panels). Note: Data were derived from isotopic plots, in which the labeled N fertiliser was applied at 30 kg N ha^{-1} at tillering of the wheat crop.

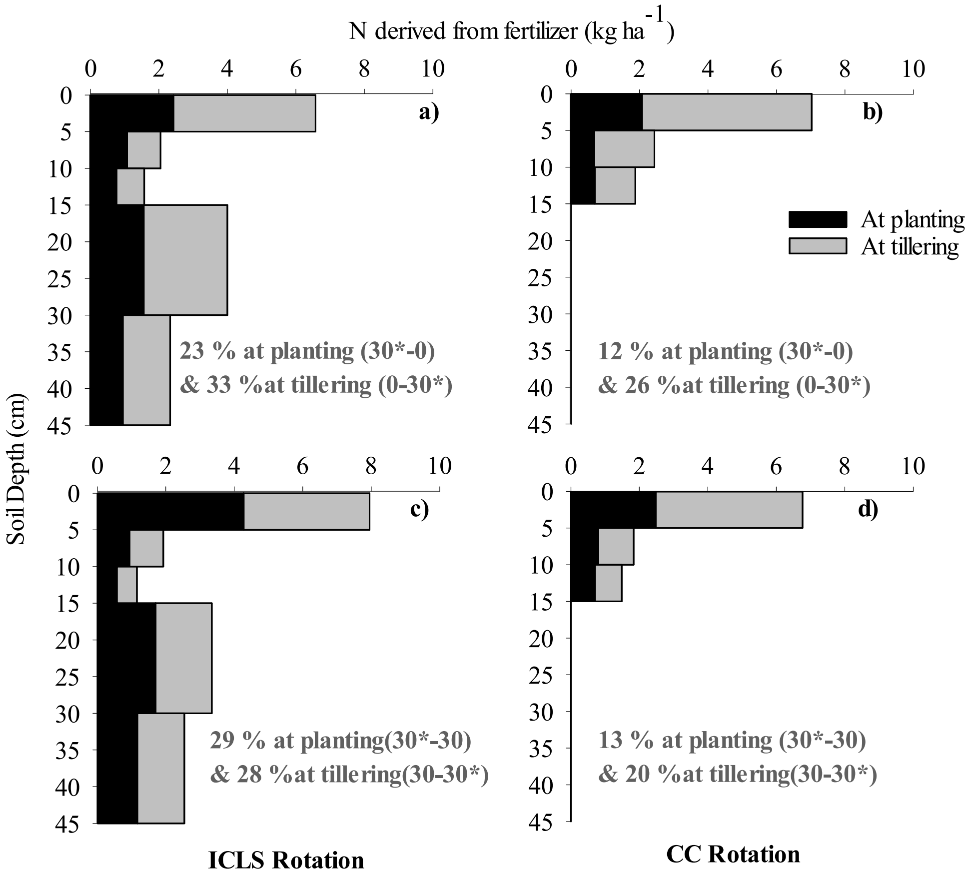

*FIG. 8. ^{15}N recovery in soil from N fertiliser applied at two N application timings (planting or tillering) and two N rate (30 or 60N) in wheat growing under CC (b and d panels) and ICLS (a and c panels) rotations. The symbol * indicates ^{15}N-labeled urea applied. The numbers in each panel show the total N recovery in soil for each N treatment and rotation system. The data set was derived from the isotopic experiment set up in 2016, applying 30 kg labeled N ha^{-1}.*

3.1.5. Main outputs from isotopic experiments

The ^{15}N recovery in the system (soil and crop) was affected by the N application timing but not by the rotation system. Then, when nitrogen fertiliser was applied at tillering ^{15}N recovery in soil and plant was higher and thus N losses lower (Fig. 9). However, it is important to highlight that ^{15}N recovery in soil under ICLS was not affected by timing of application (Fig. 8) as happened in CC, suggesting that under that rotation the N fertiliser added is potentially less available for losses.

3.1.6. Overall N balance in the wheat phase

There was no difference between rotations in the overall N balance. In both systems NB was negative at –21 and –24 kg ha^{-1} for ICLS and CC, respectively, because the difference between N recycled from N fertiliser and N outputs from soil N was similar in both systems (Table 8). A schematic diagram that explains how N balance was estimated in the wheat phase is shown in Fig. 10.

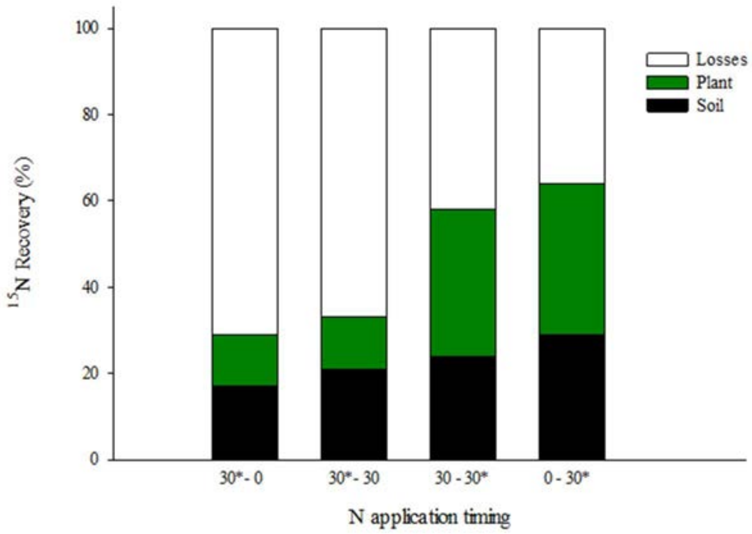

*FIG. 9. ^{15}N recovery in soil, plant and N losses from N fertiliser applied at two N application timings (planting or tillering) and two N rate (30 or 60N) in wheat growing under CC and ICLS rotation in 2016. The symbol * indicates ^{15}N-labeled urea applied. For each N treatment, ^{15}N recovery values are means of three replicates * two rotations (CC and ICLS; because the rotation effect was not significant).*

TABLE 8. OVERALL N BALANCE IN THE WHEAT PHASE IN CONTINUO CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS).

System	N	N Inputs	N Outputs		N Recycled		Total N Balance (inputs-outputs)
			Losses	Grain	Soil	Straw	
		(kgNha^{-1})					
CC	Fertiliser	30	12*	8	9	2	11
	Soil	0	2 **	33	0	0	–35
	Total	30	14	41	9	2	–24A
ICLS	Fertiliser	30	11	6	11	2	13
	Soil	0	2	32	0	0	–34
	Total	30	13	38	11	2	–21A

Note: *, N rate of ^{15}N-labeled fertiliser not accounted for; **, estimated as 20% of N losses derived from fertiliser; All values are means from three replicates and from two study years (2014 and 2016)

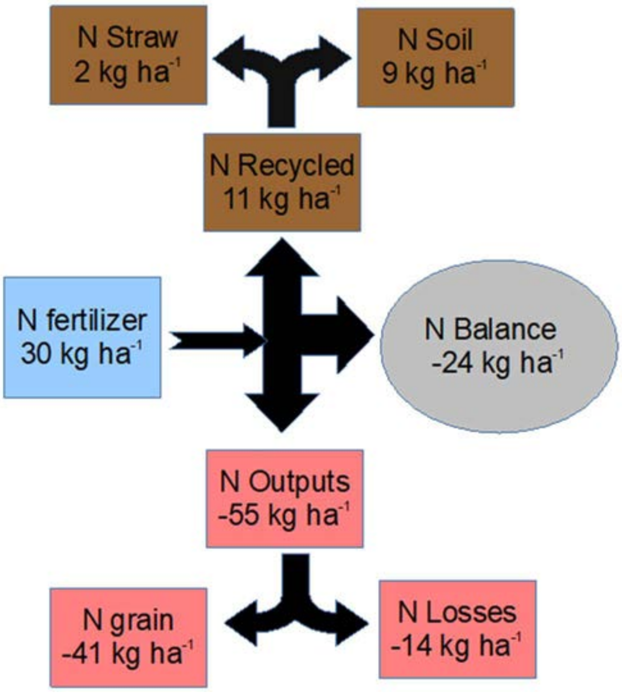

FIG. 10. Schematic of overall N balance for the wheat phase in the CC rotation. The colors used in each box match the colors used in Table 8, in which the amounts of N inputs, N recycled, and N outputs are indicated.

3.1.7. Conclusions from conventional and isotopic wheat experiments

The paradoxical result for the ICLS system, which had the lowest wheat grain yield for a soil with a high capacity to sustain higher biological productivity [23] as compared with CC, could be explained by taking into consideration the research reported by Fontaine et al. [24]. They demonstrated that soils that are building their organic reserves of nutrients and C (such as the soil under ICLS), have a shortage of plant available N due to the soil continuously sequestering nutrients (and C), and consequently a higher N response and FUE of crops planted on such soils would be expected. On the contrary, when C and N cycles are uncoupled or less coupled (such as soils under CC) there would be a microbial stimulation to mining the stable SOM reserve (increasing N release from soil which is not synchronized with plant demand), and as a result it would be likely that FUE would decrease. This outcome would lead to a greater increase in the need for surplus N additions to wheat crops grown under CC systems [25]. In conclusion, systems that combine a nutrient (and C) sequestering (pasture phase) with a SOM decomposition phase (cropping phase), would achieve better performance (increasing soil fertility and crop productivity) provided that nutrients other than N are not limiting.

3.2. Soybean Phase

3.2.1. Productivity of soybean in ICLS and CC rotations

In this phase, we could only register yield data in two years (2015 and 2016). The results were contradictory between years; in 2015 grain and grain N yield tended to be higher in ICLS than CC, but in 2016 it was the opposite, showing significantly higher grain yield in CC, ca. 900 kg ha^{-1} higher than ICLS (Table 9).

TABLE 9. PRODUCTIVITY OF SOYBEAN IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) IN 2015 AND 2016

Year	System	Replicate	Grain yield (kg ha^{-1})	Grain N yield (kg ha^{-1})
2015	CC	1	3220	166
		2	2607	133
		3	2587	136
		Mean	2804 A	145 A
	ICLS	1	3227	171
		2	3400	175
		3	3313	167
		Mean	3313 AB	171 A
2016	CC	1	3937	226
		2	3649	225
		3	4169	186
		Mean	3918 B	212 B
	ICLS	1	3383	199
		2	2777	165
		3	3001	172
		Mean	3053 A	178 AB

Note: Means followed by the same letters in the same column are not significantly different (Tukey's test, $P < 0.05$).

3.2.2. BNF estimates by isotopic techniques and their relationships with shoot dry matter, grain yield, and N uptake

The proportion of N fixed by soybean was similar in both rotations in 2015, but in the next year it was significantly lower under ICLS than CC, with 55 and 81% respectively (Table 10). The lower BNF in ICLS could be explained by the higher concentrations of nitrate-N measured in both years (Table 3). Mineral N has an inhibitory effect on N_2 fixation [7]. In addition, the amount of N fixed by soybean under ICLS was also affected by a lower shoot biomass dry matter, with a difference of ca. 1 ton ($LSD_{0.05} = 912$ kg ha^{-1}) between systems.

In the CC rotation, there was a linear relationship between grain yield and N uptake (aboveground plant) and on average across years the internal efficiency (IE) was 12.3 kg grain kg^{-1} N. This IE value was in agreement with that reported for soybean [7]. However, in ICLS a relationship between those variables was not found, implying that soybean grain yield was limited by a growth factor other than N (Fig. 11a). There was a moderately close and consistent relationship between plant N uptake and N fixed, showing that more than 80% of plant N uptake was coming from N_2 fixation (Fig. 11b). There was also a similar relationship between shoot dry matter and the amount of N fixed by soybean across both rotation and years, and around 29 kg N ha^{-1} was fixed on average for every ton of shoot dry matter accumulated (Fig. 11c).

TABLE 10. BNF IN SOYBEAN CROPS GROWING IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) IN 2015 AND 2016

Year	System	Replicate	BNF-NA†	BNF-ID‡	Average BNF
			(%)		
2015	CC	1	73	61	67
		2	84	65	75
		3	88	75	82
		Mean	82 B	67 B	74 B
	ICLS	1	71	82	77
		2	70	78	74
		3	68	64	66
		Mean	70 B	75 B	72 B
2016	CC	1	81	75	78
		2	86	77	82
		3	88	79	84
		Mean	85 B	77 B	81 B
	ICLS	1	50	53	52
		2	54	53	54
		3	62	55	59
		Mean	55 A	54 A	55 A

Note: means followed by the same capital letter within a column are not significantly different among System*years (Tukey's test, P <0.05).
†, NA, natural abundance; ‡, isotopic dilution.

3.2.3. *N balance in the soybean phase*

Rotation had a significant effect on the amount of N fixed and thus on the partial NB but N harvested in grain was similar across rotations and years (Table 11). The NB was computed in two ways: 1) considering the amount of N allocation in roots plus aboveground biomass N and 2) Only by taking into account aboveground N. For the first way, a root correction factor was used to convert aboveground biomass N into whole plant N. According to this, it was clear that the underestimation in the amount of N uptake and N fixed for not including the belowground N was significant (Fig. 12).

A linear regression was fitted between the adjusted value of N fixed and the net N input of fixed N for soybean grown in both rotations and years ($r^2 = 0.83$, $P < 0.0001$). The soybean crop could make on average a neutral N contribution to the system only if it could fix at least 150 kg N ha^{-1} (Fig. 12). The NB was estimated as the average across years, because only the rotation effect was significant ($P = 0.004$). It was positive in both systems, of 14 and 77 kg ha^{-1} when belowground N was computed. These values of NB were considered legitimate to use in the next section for estimating NB in the overall wheat-soybean sequence.

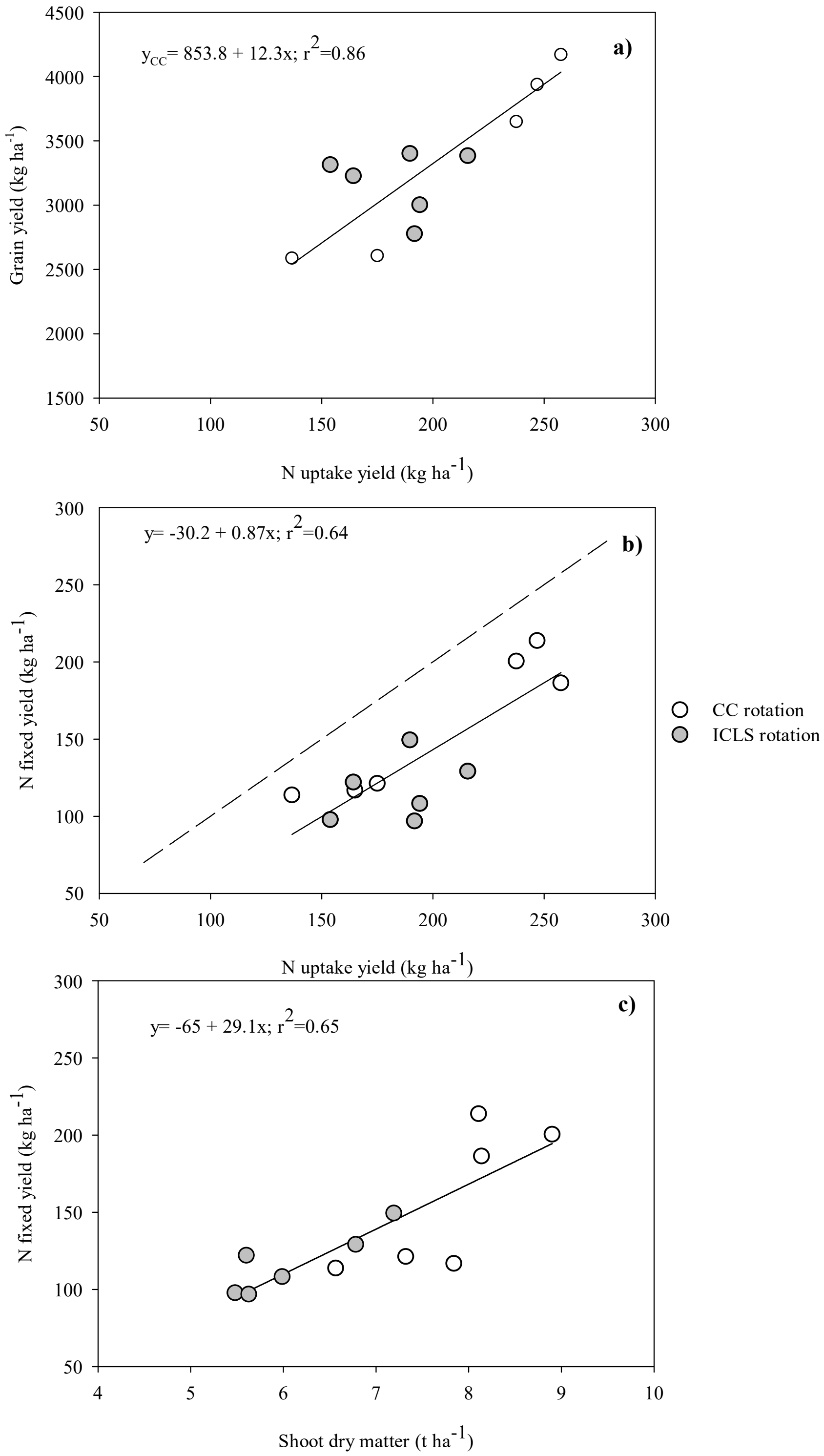

FIG. 11. Relationships between (a) N uptake (aboveground plant soybean) and grain yield (b) N fixed yield and N uptake yield and (c) and shoot dry matter for soybean growing under CC and ICLS rotations. The dashed 1:1 line represents values for which all N uptake would be expected to be derived from N air. The shoot dry matter refers to total dry matter in above-ground biomass. In panel (a) the linear relationship and model equation was made only with CC data, as there was no relationship with ICLS data.

TABLE 11. N BALANCE IN SOYBEAN PHASE IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) IN 2015 AND 2016

Year	System	Replicate	Fixed N yield	Grain N yield	N balance[†]
			(kg ha^{-1})		
2015	CC	1	117	166	–50
		2	121	133	–12
		3	114	136	–23
		Mean	117 A	145 A	–28 A
	ICLS	1	122	171	–49
		2	149	175	–26
		3	98	167	–69
		Mean	123 A	171 A	–48 A
2016	CC	1	214	226	–12
		2	200	225	–25
		3	186	186	1
		Mean	200 B	212 A	–12 B
	ICLS	1	129	199	–69
		2	97	165	–68
		3	108	172	–64
		Mean	111 A	178 A	–67 A

Note: Means followed by the same upper-case letter within a column are not significantly different among System*years (Tukey's test, P <0.05); †, N balance not corrected for root N

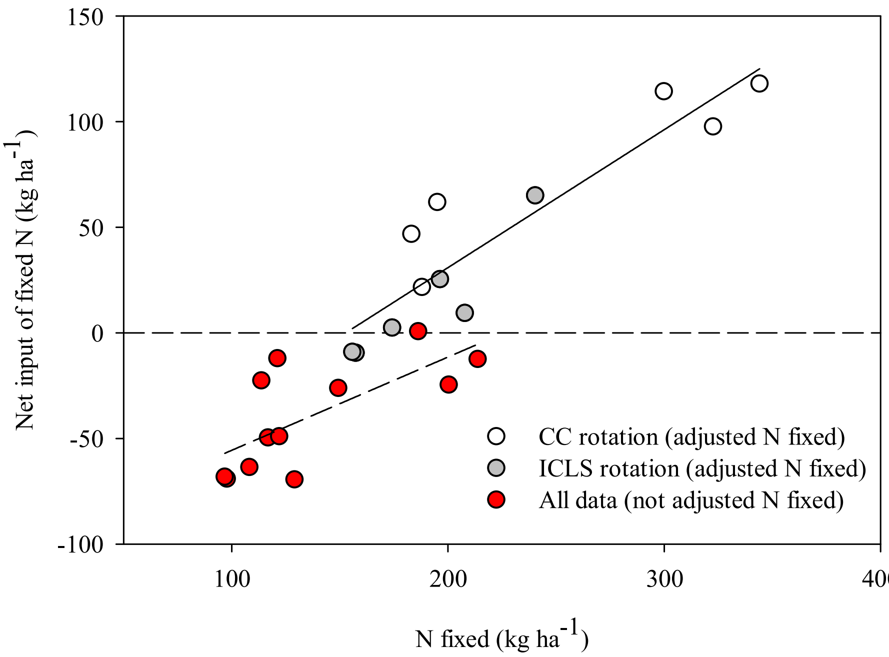

*FIG. 12. Relationships between adjusted N fixed (aboveground N fixed*root correction factor, 1.6) and net input of fixed N (adjusted N fixed – N grain harvested) for soybean grown across both rotations (ICLS and CC) and years (2015 and 2016). The solid line represents the adjusted N fixed data with a regression equation: $y = –99.7 + 0.65x$; $r^2 = 0.83$, and the dashed line correspond to the unadjusted N fixed data with a regression equation: $y = –99.7 + 0.44x$; $r^2 = 0.44$.*

3.3. PASTURE PHASE

Pasture yield was determined after a grazing event (Table 12). On average, the amount of N fixed by pasture in the first two years was close to 100 kg N ha^{-1} year^{-1}; while in the remaining year and a half it was zero because the legumes disappeared from the sward. Therefore, the annual entry of fixed N was ca. 63 kg N ha^{-1} year^{-1} (computing 3.5 years as a pasture phase).

TABLE 12. BNF, N YIELD AND FIXED N YIELD IN PASTURES GROWING IN INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) IN FOUR YEARS OF PASTURE

Pasture year	BNF	Legume in the mixture pasture	N pasture yield	N fixed
	(%)		(kg ha^{-1})	
1	89	40	60	50
2	76	81	160	130
3	90	12	90	40
4		0	50	0

3.4. N BALANCE IN OVERALL WHEAT-SOYBEAN SEQUENCE UNDER ICLS AND CC ROTATIONS

Considering that the N balance was similar in both systems in the wheat phase of –24 and –21 kg N ha^{-1} in ICLS and CC, respectively, and in the soybean phase it was positive but significant lower in ICLS than CC of 14 and 77 kg ha^{-1}, thus the annual N balance in the overall sequence was both positive and negative (53 vs. –7 kg ha^{-1}) in CC and ICLS, respectively. However, if the N input by BNF during the pasture phase was included in such estimates, the annual N balance would be similar between systems of 53 for CC and 56 kg N ha^{-1} for ICLS (Table 13).

TABLE 13. AVERAGE N BALANCE (2014–2016) IN EACH PHASE (WHEAT AND SOYBEAN) AND IN THE OVERALL SEQUENCE WITHOUT/WITH N INPUTS FROM PASTURES BNF IN CONTINUOUS CROPPING (CC) AND INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS)

	Wheat phase	Soybean phase	Overall sequence	
	Balance	Adjusted balance†	Balance without N inputs from pastures BNF	Balance with N inputs from pastures BNF
System	(kg ha^{-1})			
CC	–24 A	77 B	53 B	53 A
ICLS	–21 A	14 A	–7 A	56 A

Note: Means followed by the same upper-case letter within a column are not significantly different (Tukey test, $P > 0.05$); †, Adjusted balance includes below-ground N

4. SYNTHESIS OF RESULTS AND CONCLUSIONS

Three years of experimental data demonstrated that shifting cultivation from ICLS to CC after a long term period of change (25 years) showed either stable or higher yields under CC than the ICLS system. Wheat yields under CC were not primarily the result of the decreasing availability of N, but of declining NUE and RE, which in turn could have been caused by decreasing biological activity in the soil. Based on conceptions about NUE, we attempted to obtain insight into changes in the soil N supply and the differences between wheat response to N inputs grown under CC and ICLS systems. We also evaluated the potential environmental issues related to NUE. We suggest that although yields were lowest under the ICLS rotation, such a system had higher NUE and RE, which were mainly the result of the decreasing availability of N and other nutrients as a consequence of increasing biological activity by nutrient (and maybe C) sequestration. In this sense we have documented that sequestration into the stable C pool could be improved by adding supplementary nutrients, and that nutrient availability (N, phosphorus and sulphur) is critical to improve net humification efficiency and thus sequester C into the more stable pool of SOM.

Results from N response experiments suggested that NUE proved to be more related with RE or uptake efficiency than IE or utilization efficiency. The value of NUE in wheat grown under ICLS was high because RE tends to be high as well, whereas IE was low. However, under CC systems NUE and RE were lower than ICLS, but IE was higher. Such results indicate that under ICLS plant uptake of the applied fertiliser N was maximized and thus losses from the soil plant system diminished. However, to some extent under the ICLS rotation conditions (higher biological activity, less soil compaction, water storage capacity, etc.) were promoted, so that N applied was conserved in the cropping system as a whole. This was reflected also in ^{15}N recovery of the soil, which was similar in either of the N application times (planting and tillering), and then if a high amount of N was captured, there would be less potential for losses. In conclusion, systems that combine a nutrient (and C) sequestering phase (pasture phase) with a SOM decomposition phase (cropping phase), would overall achieve a better performance (increasing soil fertility and crop productivity), provided such a system included balanced plant nutrition on space and time. This system of land management is currently a potential tool to contribute to atmospheric carbon dioxide remediation and mitigation of climate change.

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THE ROLE OF INTEGRATED CROPPING-LIVESTOCK SYSTEMS (ICLS) IN CLIMATE SMART AGRICULTURAL PRACTICES

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Abstract

Continuous nutrient mining, monocropping and poor farming practices are still norm in many developing countries, and they generally lead to declining soil fertility and quality, and loss of crop productivity and falling income. For sustainable crop production, farmers, especially in developing countries, require to be equipped with the knowledge of how to maintain and even improve soil fertility through best farming practices and increasing crop production with lower environmental footprints. Integrated cropping-livestock system (ICLS) has the most potential to enrich soil with essential plant nutrients, sequester carbon and increase crop productivity. Farmers need to take holistic approach by adopting the different models of ICLS (i.e. growing nitrogen fixing legumes in rotation, recycling of organic residues and manure and animal grazing to minimise their dependence on chemical fertilisers), strategic use of chemical fertilisers and water, and unnecessary cultivation to preserve carbon and nutrients in soil.

1. INTRODUCTION

Soil, which is a living body, plays an essential role in food security (i.e. producing crops, fruits and vegetables), grazing lands for animals, and supporting biodiversity. Commercial farming operations are often based on monoculture practices, in which soil is used to grow the same crop for multiple years or growing seasons and require excessive amounts of synthetic fertilisers. Monoculture result in lower soil fertility and thus reduced crop yields over time, and the production and use of synthetic fertilisers releases large quantities of greenhouse gases (GHGs), which contribute to climate change.

Under the changing climate, the biggest challenge that farmers face is to improve and maintain soil fertility while increasing agricultural productivity with lower environmental footprints (i.e. low emission of GHGs). Increased emissions of anthropogenic GHGs are involved in causing extreme weather events such as droughts, flooding, and rising temperatures in the atmosphere. These negative effects of climate change, along with others, impede the ability of agricultural systems to produce enough food to meet the demands of the growing human population and thus lead to global food insecurity. The three main GHGs influenced by anthropogenic actions are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The agricultural sector contributes globally to approximately 25% of CO_2, 50% of CH_4, and 70% of N_2O emissions [1].

The Soil and Water Management and Crop Nutrition Section of the joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture of the UN helps Member States to develop climate smart agricultural practices to enhance global food security by achieving high crop yields in a sustainable manner. It does so through the adaptive research and development at its own laboratory in Seibersdorf as well as the organization of Coordinated Research Projects (CRPs) involving research institutions and experimental stations in Member States. Climate Smart Agricultural Practices focus on food security, adaptation, and mitigation of GHGs.

Among the Climate Smart Agricultural Practices, integrated cropping-livestock systems (ICLS) are one of the simplest and highly beneficial practices that could enrich soil with essential plant nutrients, improve soil organic matter and soil biological activities, thus leading to increasing soil fertility, and improvement in soil structure, and stability. Though ICLS generally require greater capital and labour inputs than simplified systems, they present similar or higher profits [2 and 3].

To achieve these positive effects, farmers could stop poor farming practices such as monocropping and take holistic approach by adopting the principles of ICLS (i.e. growing nitrogen fixing legumes in crop rotation, recycling of organic residues and manure and animal grazing to minimise their dependence on chemical fertilisers), strategic use of chemical fertilisers and water, and unnecessary cultivation to preserve carbon and nutrients in soil. Integrated cropping-livestock systems help conserve nutrients and thereby provide better growing environments for crop growth and enhanced crop productivity. In an integrated cropping-livestock system, farmers either use animals to graze the field crops or feed the crop residue to livestock after harvesting. They then collect the manure from the livestock to be used as fertiliser, thereby returning the nutrients to the soil.

The aim of the Coordinated Research Project "Optimizing Soil, Water and Nutrient Use Efficiency in Integrated Cropping-Livestock Production Systems (D1.20.12)" was to investigate mutually beneficial synergies in the production of crops and livestock for human consumption. In modern intensive agricultural systems, crop and livestock husbandries are often conducted as separate enterprises. However, traditional small-scale agriculture was based on the raising of crops and livestock on the same family farm. Many advantages can accrue from side by side crop-livestock farm activities. For example, protein-rich grain legume residues or cereal straw can be fed to livestock, while livestock manure can be used as fertiliser for crops. In this CRP, the opportunities for obtaining benefits from integrated cropping-livestock production systems were investigated, with the aid of strategically applied nuclear techniques to obtain unique information on soil-plant-animal interactions. Studies from six countries on three continents including Argentina, Brazil, India, Kenya, Uganda and Uruguay are presented in this report. A summary of the results from the studies indicated that by adopting ICLS, farmers in Argentina, Brazil, India, Kenya and Uruguay increased their crop yields, enhanced soil fertility and quality in an environmentally friendly fashion.

The studies conducted over five years indicated that ICLS has the most potential to lower the environmental footprint of agriculture by emitting less GHGs, increasing soil fertility, enhancing crop productivity, and improving animal health in a cost effective way. It is clear that poor farming practices (i.e. monocropping) ought to be stopped in favour of the adoption of sustainable ICLS principles, such as: recycling of organic residues and manure, growing nitrogen fixing legumes in rotation, and animal grazing: all to reduce dependence on chemical fertilisers. Other ICLS principles include the strategic application of fertilisers (i.e. in the correct amount, at the proper growing stage, in the right manner) and water and minimal tillage to reduce losses of soil carbon and other nutrients.

Scientists in Argentina have found that an ICLS is ideal for cultivating crops to be more resilient to the effects of climate change. They have benefited from this project by improving their agricultural soils with crop-pasture rotations in conjunction with conservation tillage systems and observed a 50% increase in organic carbon content in the soil, which enhances the resilience of the cropping system to climate change that affect crop yields.

FIG. 1. Soil sampling in Argentina.

In Brazil, scientists are looking for ways to maximize land use efficiency, and research into the effectiveness of using an integrated cropping-livestock system has brought positive results. They are moving towards the implementation of conservation agriculture, and have seen the feasibility of such an approach involving integrated cropping-livestock systems. As a result of the use of this method, GHG emissions from livestock excreta (urine and dung) have been reduced by 89% compared to the default value set by the Intergovernmental Panel on Climate Change (IPCC).

FIG. 2. Open grazing cattle in Brazil.

The researchers in India were able to maintain rice yields and soil fertility through the use of farmyard manures along with phosphorus and potassium, in place of synthetic nitrogen fertilisers. Additionally, by feeding the fodder grown in nutrient recycled fields to goats and dairy cows, the productivity of the animals significantly improved. Over 5 years, the birth and weaning weights of calves increased by 20% and 10% respectively. The milk production of adult dairy cows also improved by at least 11% as compared to the first year.

FIG. 3. Grazing dairy cows in India after rice harvest.

Research on ICLS in Kenya spiked due to falling yields as a result of declining soil fertility and climate variability. These recent developments are especially critical considering the rapidly growing population in many Kenyan regions. In order to ensure food security it is critical to investigate methods to improve water and nutrient use efficiency and increase yields in the predominantly arid and semi-arid climate. By using an intercropping system and applying a mixture of farmyard manure with microdosed inorganic fertilisers, scientists found that higher biomass and grain production can be achieved. However, yields continue to vary significantly between the short and long bimodal rainy seasons.

Improving and implementing ICLS in Uganda is especially important because the access to inorganic fertilisers is extremely limited due mainly to affordability for farmers. Scientists were able to produce higher maize yields in a cultivation-grazing rotation, as compared to continuous cropping, and recommend a maize-grazing rotation on the fertalitic soils of central Uganda under limited fertiliser access. They also found that the pool of soil organic matter increased in the ICLS system, which is important for overall and long-term soil health and fertility.

In Uruguay, there has been an evident shift towards intensification and simplification of farming practices (i.e. continuous cropping). Researchers found that the nitrogen use and recovery efficiencies of plants in ICLS was higher than in continuous cropping, and factors other than nitrogen effect crop productivity. The study emphasized that though yields can be higher in continuous cropping, there is a long term elevated risk of nitrogen losses. This suggests that ICLS is the more sustainable agricultural method in the long run.

ICLS, when practiced properly leads to many benefits, however, improper practices can have numerous consequences. For example, excess application of farmyard manure or other nutrients results in eutrophication. These excess nutrients can enter nearby water bodies and cause low dissolved oxygen, eutrophication, and algal storms, which often result in fish kills.

To further prevent malpractice and improve ICLS the following technologies could be explored: input and management based technology, accelerating and diffusing technology, exogenous and indigenous technologies, technologies for national and local problems, technologies for individual farmers and for society, and exploitative regenerative technologies. Overall the diverse operations of ICLS reduce risk of failure, despite any one component being negatively affected as in monoculture. Additionally, ICLS can provide a more stable and diversified source of income throughout the year versus continuous crop or livestock production [2] Brochures with the known ICLS best practices for farmers, which are highlighted in this TecDoc, would be beneficial for developing countries in the implementation of CSA and in the building of a climate resilient and food secure future.

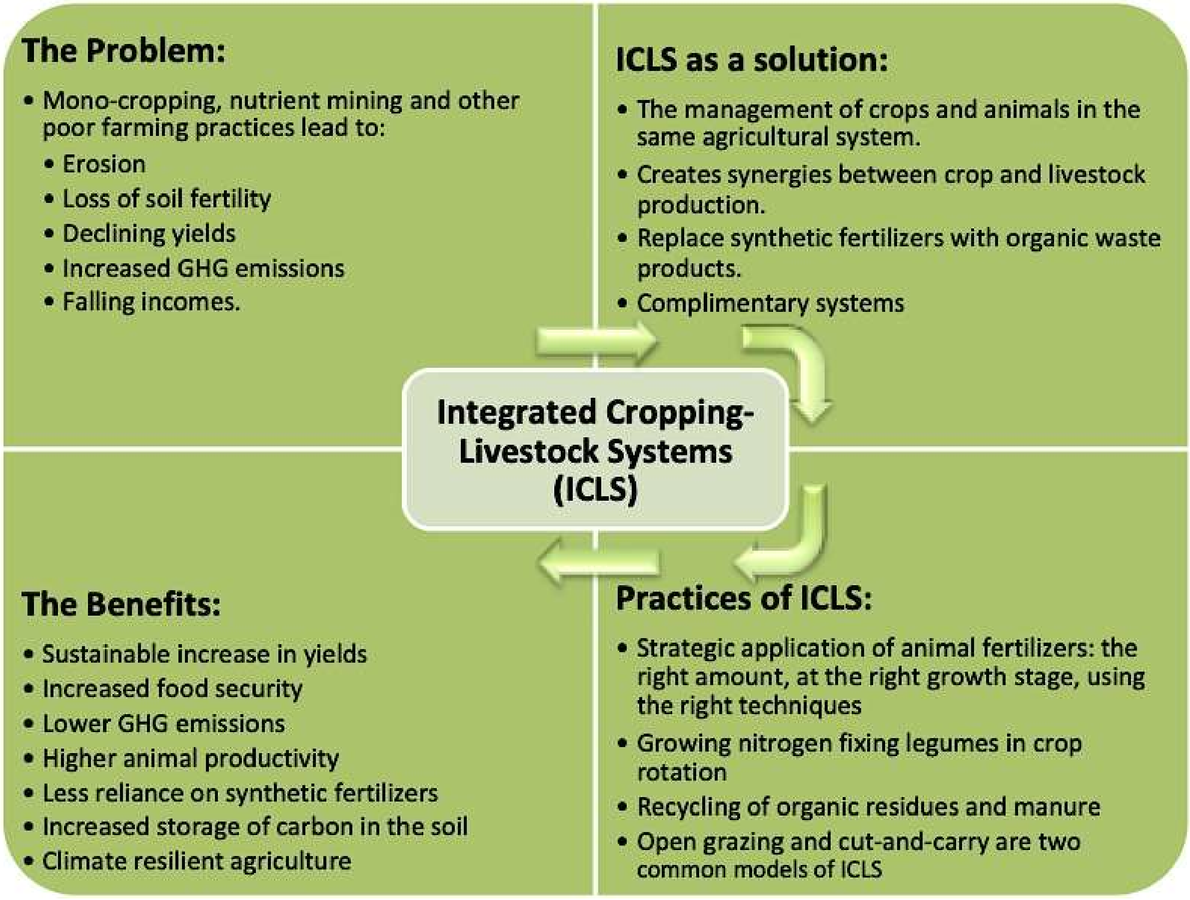

FIG. 4. Schematic diagram of ICLS

2 MAIN TYPES OF ICLS

Model 1.

In this type of ICLS (Fig 5) , the crops are either cut and carried to the animal housing for feeding the animals. The crops are harvested and/or fed to the livestock, followed by collecting animal manure which is then directly applied as fertiliser for crops. It is also common practice to allow livestock to graze directly on crop residues on fields after harvest.

FIG. 5. Model 1. Reproduced courtesy of Tamil Nadu Veterinary and Animal Sciences University [4]

Model 2.

This model of ICLS (Fig 6) combines fish farming with poultry and crops. The poultry litter is provided as feed to fishponds to promote fish growth. The pond water, which is nutrient rich, is then used to both water and fertilize crops. Crops are harvested and residues are fed to poultry and other livestock animals.

FIG. 6. Model 2. Reproduced courtesy of Tamil Nadu Veterinary and Animal Sciences University [4]

Model 3.

A third system of ICLS (Fig 7) is cut and carry with vermicomposting. Animal manure is collected and vermicomposted before field application. The resulting harvested crops/crop residues are then carried and fed to livestock.

FIG. 7. Model 3. Reproduced courtesy of Tamil Nadu Veterinary and Animal Sciences University [4]

Model 4.

This model of ICLS (Fig 8) involves housing pigs above fishponds to supply the nutrient rich manure to support fish growth. The pond water is then used to fertilize and water crops, which are harvested and fed to the pigs.

FIG. 8. Model 4. Reproduced courtesy of Tamil Nadu Veterinary and Animal Sciences University [4]

Model 5.

Another model of ICLS (Fig 9) allows poultry to feed on forage. The droppings from the poultry directly fertilize the forage areas, which encourages continued growth. Excess droppings can also be collected and applied to field crops.

FIG. 9. Model 5. Reproduced courtesy of Tamil Nadu Veterinary and Animal Sciences University [4]

Model 6.

An additional ICLS model (Fig 10) utilizes the behaviour of goats, who tend to waste protein rich feed by spilling. Therefore, when goats are raised in elevated platforms above poultry, the spilled feed will be consumed by the poultry. Animal manure is also collected and used as fertiliser for crops, which can be fed to livestock and humans.

FIG. 10. Model 6. Reproduced courtesy of Tamil Nadu Veterinary and Animal Sciences University [4]

Model 7.

A final model of ICLS (Fig 11) takes advantage of animal manure and farm waste waters to support horticulture and fodder crops. The resulting horticulture residues and fodder crops are then fed to livestock.

FIG. 11. Model 7. Reproduced courtesy of Tamil Nadu Veterinary and Animal Sciences University [4]

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ABBREVIATIONS AND ACRONYMS

Al	Aluminium
ANOVA	analysis of variance
ASAL	arid & semi-arid lands
B	bare ground
BNF	biological nitrogen fixation
C	Carbon
Ca	Calcium
CC	continuous cropping
CA	conservation agriculture
CAN	Calcium Ammonium Nitrate
CEC	cation exchange capacity
CH_4	Methane
cm	centimetre
CO_2	Carbon Dioxide
$Co(CN)_4$	Tetracyano Cobaltate
CRP	coordinated research project

CT	conventional tillage
D	dung
DAP	Diammonium Phosphate
DCD	Dicyandiamide
D-DCD	Dicyandiamide sprayed on dung patch
D-DCDd	Dicyandiamide dissolved into dung
DM	dry matter
DMI	dry matter intake
DW	dry weight
ECe	electrical conductivity
ECD	electron capture detector
EF	emission factor
FAO	Food and Agriculture Organization of United Nations
FID	flame ionization detector
FTP	full term parturition
FYM	farm yard manure
FW	fresh weight

g	gram
GC	grazing continuous treatment
GHGs	greenhouse gases
H	Hydrogen
ha	hectare
H_2O	water
IAEA	International Atomic Energy Agency
ICLS	integrated cropping-livestock system
IE	internal efficiency
ILF	integrated livestock-forest system
IPCC	Intergovernmental Panel on Climate Change
IRMS	isotope ratio mass spectrometer
K	Potassium
KCB1	katumani composite 1
KCl	Potassium chloride
Kg	kilogram
L	litre

LR	long rains
LSD	least significant difference
MAM	March to May
MC	maize continuous
MCF	maize continuous fertilised
m	million
mg	milligram
Mg	Magnesium
MG	maize grazing
MOC	Mineral Organic Carbon
MoL&F	Ministry of Agriculture and Livestock and Fisheries
mt	million tonnes
N	Nitrogen
NB	Nitrogen balance
NEB	negative energy balance
NG	native grassland
Ndff	N derived from fertiliser

NH_3	Ammonia
NO_3^-	Nitrate
N_2O	Nitrous oxide
NPK	Nitrogen, phosphorus and potassium fertiliser
ns	not significant
NUE	Nitrogen use efficiency
OND	October to December
P	Phosphorus
PDB	pee dee belemnite
POCc	particulate organic carbon-coarse
POCi	particulate organic carbon-intermediate
POM	particulate organic matter
PPH	post-partum heat
PVC	Polyvinyl chloride
RCB	randomised complete block
RCBD	randomised completed block design
REF	reference soil under natural vegetation

SOC	soil organic carbon
SOM	soil organic matter
SON	September to November
SRI	system of rice intensification
SSA	Sub-Saharan Africa
SWMCN	soil and water management & crop nutrition
t	tonne
TANUVAS	Tamil Nadu Veterinary and Animal Sciences University
TDN	Total Digestible Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TSP	Triple Superphosphate
U-DCDd	Urine With Dicyandiamide Dissolved
WFPS	water-filled pore space

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