



Concept Paper

The ‘Palo a Pique’ Long-Term Research Platform: First 25 Years of a Crop–Livestock Experiment in Uruguay

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Abstract: Mixed crop–livestock long-term experiments (LTE) are critical to increase the understanding of sustainability in complex agroecosystems. One example is the ‘Palo a Pique’ LTE which has been running for 25 years in Uruguay (from 1995 to present), evaluating four pasture–crop rotations under livestock grazing with no-till technology in soils with severe limitations. The results demonstrate that cropping systems reduced soil organic carbon (SOC) compared with permanent pastures, and that perennial pastures rotating with crops were critical to mitigate SOC losses. Data from the ‘Palo a Pique’ LTE has contributed to the establishment of new national policies to secure the sustainability of agricultural-based systems. Although the original purpose of the LTE was oriented to crops and soils, a demand for sustainable livestock intensification has gathered momentum over recent years. As a result, the current approach of the ‘Palo a Pique’ LTE matches each pasture–crop rotation with the most suitable livestock strategy with the common goal of producing 400 kg liveweight/ha per year. General approaches to the pursuit of sustainable livestock intensification include shortening the cycle of production, diversifying animal categories, increasing liveweight gain and final animal liveweight, and strategic livestock supplementation. Prediction of trade-offs between environmental, economic, and production indicators can be addressed through monitoring and modeling, enabling the timely anticipation of adverse sustainability issues on commercial farms. The ‘Palo a Pique’ LTE serves as a framework to address contemporary and future questions dealing with the role of ruminants on climate change, competition for land, nutrient dynamics, and food security.

Keywords: crop–livestock; pasture–crop rotations; sustainability; sustainable intensification; long-term experiments

1. Introduction

Long-term experiments are critical to increase our understanding of the sustainability of agroecosystems [1], where sustainability must be tackled across its three core dimensions, i.e., economic, environmental and societal [2]. The larger spatial and longer temporal scales of a long-term experiment (LTE) capture complex processes that might confound or be overridden in small-scale experiments with reductionist frameworks [3]. For instance, LTEs are essential in determining soil-related factors affecting the sustainability of production systems and in estimating key performance indicators (KPIs)

for the characterization and prediction of outcomes [4,5]. This is critical for agriculture and livestock systems gripped in a debate around their environmental impact and the competition between livestock feed and human food for arable land use (feed vs. food) [6].

Despite acknowledging the value of long-term research to answer questions related to sustainability [7], integrated crop–livestock LTE research presents several challenges. In a review article, Tanaka et al. [8] discuss the requirement of many hectares and labor resources for the experiments, the need for expensive budgets secured over time, the requirement of a multidisciplinary team and the short-term requirement of producing scientific publications. Further, some have lacked sufficient replication, entailing questionable statistical analyses. On the other hand, LTEs create a realistic comparison with commercial systems, at credible (spatial and temporal) scales, and, ideally, with active participation from farmers [9].

Crop–livestock systems in Uruguay include 4905 farms corresponding to 2,519,000 ha [10]. Approximately, this represents 10% of the total livestock producers in Uruguay (excluding dairy operations) and 17% of the total land used by livestock [10]. The expansion of mixed crop–livestock systems has occurred despite land tenure limitations, where crop and livestock farmers engage with each other via a short-term leasing contract in a ‘symbiotic’ relationship [11]. Low productivity of natural grasslands, increased crop yield after a period of seeded pastures and reduction of soil erosion were the main reasons for the adoption of pasture–crop rotation under no-till technology in Uruguay in the second half of the 20th century [12]. Derpsch et al. [13] stated that Uruguay is one of the few countries that have engaged in permanent no-tillage practices. Thus, Terra and García Préchac [14] posed the following research question: “Can no-till technology and pasture–crop rotations allow sustainable agricultural intensification in marginal soils in eastern Uruguay”? These researchers pointed out the need for a LTE, as the cumulative effects of no-till pasture–crop rotations in grain yield and soil fertility need to be observed over extended periods and are affected by climatic variability. To answer this question, they set up the ‘Palo a Pique’ LTE, which continues today as one of the longest running pasture–crop LTEs in the world.

The LTE evaluating four different pasture–crop rotations in Treinta y Tres (Uruguay) at the National Institute of Agricultural Research (INIA) Palo a Pique Research Unit (33°15′54.4″ S 54°29′28.1″ W, Figure 1), is among the longest running field experiments in the region. Examples of long-term agricultural platforms in the region are the pasture–crop rotation experiments established in 1976 at Balcarce in Argentina [15] and in 1985 in Rio Grande do Sul in Brazil [16]. In Uruguay, there are three LTEs comparing soil use and management alternatives in temperate regions: INIA ‘La Estanzuela’ (1963–present), INIA ‘Palo a Pique’ (1995–present), and Faculty of Agronomy Estación Experimental ‘Dr. Mario A. Cassinoni’ (EEMAC), Universidad de la República (1993–present) [17]. The LTE at INIA La Estanzuela evaluates seven cropping systems differing in the amount of time spent under pasture, ranging from continuous cropping (with and without fertilization) to a rotation of two years of crops and four years of pastures [18,19]. The LTE established at Faculty of Agronomy compares four treatments in a factorial combination of two cropping systems (continuous cropping and crop–pasture rotation) and two tillage systems (conventional tillage and no-till) [20,21]. Some of the treatments among LTE in Uruguay are comparable, but the ‘Palo a Pique’ LTE is the only one including livestock grazing of the experimental units, mirroring commercial conditions. The ‘Palo a Pique’ LTE is part of the ‘Global Farm Platform’ (www.globalfarmplatform.org), a global initiative that brings together diverse farm platforms working ‘towards sustainable ruminant production’ under a wide range of environmental and productive circumstances across five continents of the globe [22].

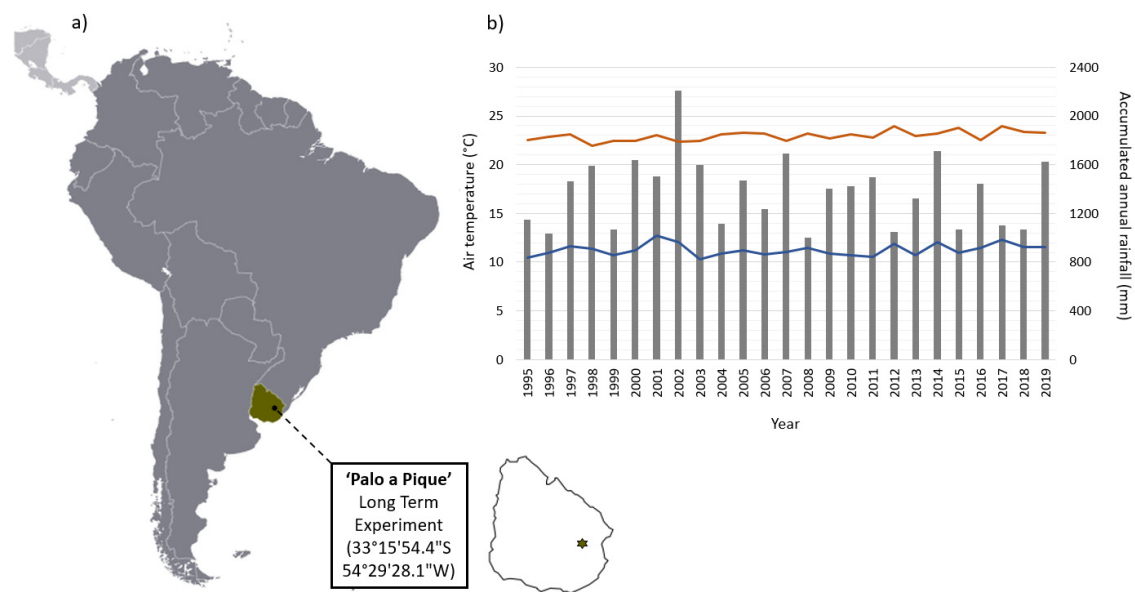


Figure 1. Location of the 'Palo a Pique' long-term experiment of the National Institute of Agricultural Research (INIA) in Uruguay (a), and annual accumulated rainfall (grey bars), mean maximum air temperature (orange line) and mean minimum air temperature (blue line) from 1995 to 2019 (b).

Despite the scientific and demonstrative value of the 'Palo a Pique' LTE, it is not well known worldwide. Thus, the objectives of this article are to: (i) describe the origin and evolution of the LTE; (ii) show some key findings and the impact on agricultural policies, and (iii) describe current goals and challenges of the 'Palo a Pique' LTE.

2. Origins and Evolution of the 'Palo a Pique' Long-Term Experiment

The evolution of the 'Palo a Pique' LTE can be explained in three phases which are described below and summarized in Figure 2.

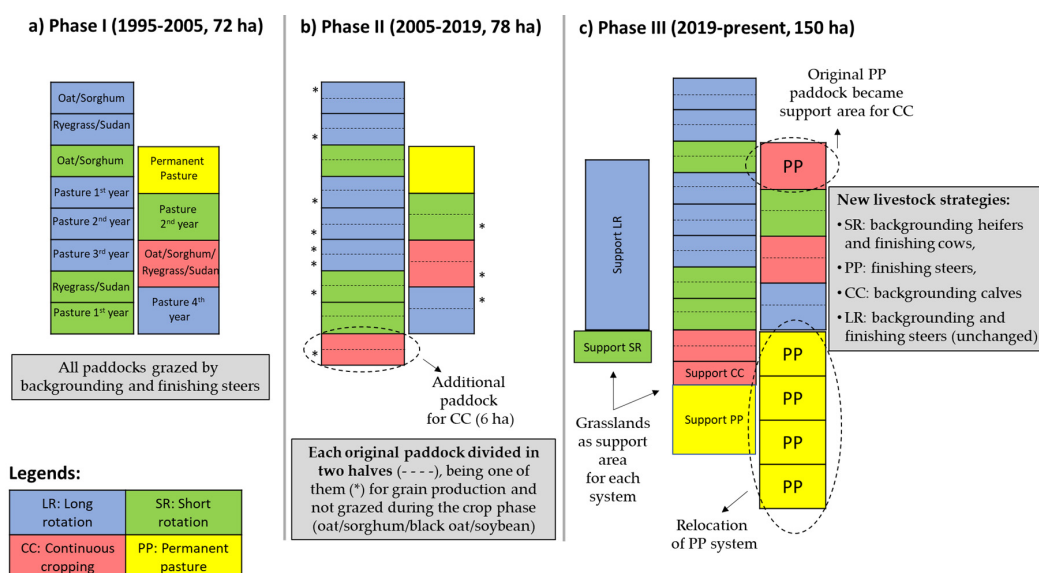


Figure 2. Field plot layout showing experimental design and chronological changes of the 'Palo a Pique' long-term experiment. Treatments: long rotation in blue (LR, two years of crops followed by four years of pastures); short rotation in green (two years of crops followed by two years of pastures); permanent improved pasture in yellow (PP); and continuous cropping in red (CC). All the phases of the rotations are present each year (the plot layout shown in Phase I represents an example of one particular year).

2.1. Phase I—The Beginning (1995–2005)

In 1995, four pasture–crop rotations (Figures 2a and 3) were established over 72 ha on slightly degraded soils under renewed natural grasslands at the ‘Palo a Pique’ Research Unit (INIA, Uruguay), after a few years of annual cropping with tillage. The rotations compared under no-till were: long rotation (LR, two years crops and four years pastures); short rotation (SR, two years crops and two years pastures), continuous cropping (CC, without pastures), permanent pasture (PP, without crops). The annual mean (\pm SEM) accumulated rainfall for the last 25 years (1995–2019) was 1379 ± 58 mm per year with no seasonality within the year, whilst the mean maximum and minimum air temperatures for the same period were 23.0 ± 0.1 °C and 11.3 ± 0.6 °C, respectively (January is the warmest month, averaging 23.0 ± 0.5 °C, whilst July is the coldest month, averaging 10.9 ± 0.9 °C) (Figure 1). The dominant soils are Typic Argiudols with low to moderate soil fertility (1.5 to 2.0% soil organic carbon content (SOC), mass base, in 20 cm depth). They occupy a landscape of gently sloping hills of modest altitude, where the erosion risk is moderate to high [23]. Moreover, because of a strongly developed argillic B horizon, these soils are somewhat poorly drained. Given such natural limitations, they are classified between land capabilities III and IV in the United States Department of Agriculture (USDA) Land Capability Classification [23]. As each rotation treatment needed to have the same initial potential, each paddock had similar drainage and topographic features.

Rotation characteristics and grazing management have been extensively described by Terra et al. [24] and are provided in the Supplementary Materials (Supplementary Material S1). Each phase of the rotations was represented by a paddock of 6 ha, which was the experimental unit (EU), totaling 12 EUs. Paddock size is one of the strengths of ‘Palo a Pique’ LTE, because it is large enough to use commercial machineries during the crop phase (seeding, harvesting, etc.) and to produce the amount of feed required to sustain a certain number of animals to collect representative data, but small enough to minimize crop production within paddock variability [8]. Although all phases of the rotations were present at the same time, there were no synchronic replications of each phase [24]. Soil samples were annually collected from three different topographical areas within each paddock: top of the hill, moderate slope and lowland at the end of the slope. For the main variable, SOC, the experiment was analyzed as a complete block design with three replicates where the topographic zones acted as pseudo-blocks [23]. For pasture and animal variables, the year (cycle of production) was considered as a replicate.

Year 1		Year 2		Year 3		Year 4		Year 5		Year 6	
F-W	Sp-S	F-W	Sp-S	F-W	Sp-S	F-W	Sp-S	F-W	Sp-S	F-W	Sp-S
WC ₁	SC ₂	WC ₃	SC ₄	PP ₁	PP ₁	PP ₂	PP ₂	PP ₃	PP ₃	PP ₄	PP ₄

Long Rotation (LR)

WC ₁	SC ₂	WC ₃	SC ₄	PP ₁	PP ₁	PP ₂	PP ₂
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Short Rotation (SR)

WC ₁	SC ₂
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Continuous Crop (CC)

PP

Permanent Pasture (PP)

Figure 3. Original design of the pasture–crop rotations under no-till technology in the ‘Palo a Pique’ long-term experiment (1995). F: fall; W: winter; Sp: spring; S: summer; WC: winter crop (*Lolium multiflorum* L., *Avena strigosa* L.); SC: summer crop (*Sorghum bicolor* L., *Setaria italica* L.); PP: permanent improved pasture re-seeded every 5 years. Numeric subscripts (1,2,3,4) means the sequential order of the crops or pasture age. Orange and green boxes represent the crop and pasture phase, respectively. Each rectangle covering one year corresponds to a 6 ha paddock.

2.2. Phase II—Crop Intensification (2005–2019)

In the early 21st century, a new cropping intensification model started in Uruguay based on soybean (*Glycine max* L.). The rapid increase in food processing [25], the widespread use of transgenic cultivars and the massive adoption of no-till technology as a farming practice led Uruguayan agriculture to change from traditional pasture–crop rotations to continuous cropping dominated by soybean or soybean–wheat (*Triticum aestivum* L.) rotations [26]. This resulted in a reduction in the duration of the pasture phase in the rotation or even its removal, raising questions about the sustainability of such a productive model due to soil erosion risk and associated SOC losses [27]. It has been demonstrated that declining crop diversity and concentrating rotations on a few selected crops is neither profitable for producers nor good for the environment in the long-term [8].

To address this need, 11 out of the 12 EU of the original LTE (those rotating with crops) were split in half in 2005 (3 ha each) and grain crops were included in one half during the cropping phase ('grain rotation', GR) (Figure 2b). Animals were excluded from the 3 ha paddock during the cropping phase, and the crops were oriented for grain production by including soybean and wheat in the rotation, which were commercialized after harvesting. On the other hand, sorghum and hay remained in the systems for livestock supplementation. Therefore, by adopting this crop combination, grains with lower nutrient concentration for human nutrition (sorghum) and feed that humans cannot eat (hay) were converted into nutrient-dense food such as beef meat. The other half of the paddocks were maintained with the same pasture–crop rotation described in Phase I intended for livestock grazing.

Later, in 2012, a second 6 ha paddock was incorporated to the CC rotation (Figure 2b). Hence, the three rotations having crops (CC, SR, and LR) could have a cycle represented by a sequence of four crops in two paddocks. Previously, that was true only for SR and LR, but CC had only a cycle of two crops in one paddock.

2.3. Phase III—Land Expansion and Livestock Intensification (2019 to Present)

All adjustments made in Phase III are highlighted in Figure 2c. At the same time as the LTE was being redesigned, a six-year-old grazing experiment was coming to an end in the 'Palo a Pique' Research Unit. This trial aimed to compare animal performance, pasture persistence and productivity of two cultivars of tall fescue (cv. INIA Aurora and INIA Fortuna) with or without the addition of a domesticated endophyte (AR584) with high inputs of urea [28]. It was proposed that there were significant benefits in combining the two experiments by incorporating the tall fescue area (24 ha) into the LTE. The five 4.8 ha paddocks of tall fescue pasture replaced the paddock of PP (6 ha) in the original design of the LTE. This decision increased the scale, breadth and depth of the LTE as more paddocks were available for grazing in the PP system.

In a second modification, the original 6 ha paddock of PP was combined with the CC rotation (with PP added to the support area, as explained below). Thus, both treatments maintained their independence in terms of land use, keeping the original design under no-till technology, but, from then on, would be managed as a single animal production system. This is more realistic compared with commercial farms, where cropping is usually performed in areas with higher soil fertility and livestock activities are carried out on pastures in soils with less potential outside the crop rotation. This also allowed the quantification of the environmental impacts of cropping and livestock separately. Moreover, the original 6 ha paddock of PP now included in the CC system (as the supporting area) is still managed with grazing livestock and the soil organic carbon has been monitored since 1995. It is still the "control" for continuous permanent pasture areas. Therefore, we think this change does not affect the main contrast (soil organic carbon in pasture vs. continuous crop vs. pasture–crop rotations) that started in 1995, as the original pasture-based paddock remains as such.

The third adjustment was the addition of a support area of natural grasslands for each rotation. This area was not part of the pasture–crop rotation but allowed greater flexibility in livestock management in each rotation, maintaining animals within the experimental domain. Previously, animals were managed in the rotations under a 'put and take' protocol depending on forage availability and

soil conditions. When forage was scarce, or soil conditions were too wet for grazing, animals were taken to a common area outside the rotation, and then re-entered when the conditions improved. With this change, each rotation had an independent external support area to handle the animals when necessary, avoiding co-grazing the animals coming from the different rotations (and associated statistical confounders). For that reason, it is now appropriate to change the reference of the treatments from 'rotations' to 'systems', as each of the four systems was totally closed and independent from the land and livestock management standpoint, and the rotations did not occupy 100% of the area. This allows for a better environmental comparison as the nutrients excreted in the feces and urine of the animals are recycled within the boundaries of each system and mirror commercial farms where support areas composed by natural grasslands play an important role in grazing management, even in intensive pasture–crop rotations. As noted by Scott et al. [9], the system boundaries of farmlet experiments need to be established in such a way that transfers between systems are minimized.

In addition, the best livestock strategy was defined for each pasture–crop rotation. Previously, all rotations had the same orientation: the backgrounding of calves and finishing of steers for 18–20 months. This strategy favored the rotation with a greater proportion of pastures and number of paddocks to handle the two categories of animals but impaired the shorter rotations with lower carrying capacity in fall and spring due to pasture and annual forage sowing. Moreover, animals were used to control pasture growth rather than to collect performance data. In the new design, the original pasture–crop rotations were maintained, but the focus and efforts for data collection moved from concentrating solely on soil and crops to incorporating pasture and livestock performance.

The new livestock strategies had to meet three criteria to: (i) be able to produce 400 kg liveweight (LW)/ha per year ($\pm 10\%$), (ii) be commercially available and adopted by producers (to end up with an animal category that is easy to sell), and (iii) be different from each other (preferably).

Each new livestock strategy designed for CC (backgrounding calves), SR (backgrounding heifers and finishing cows), and PP (finishing steers), compares the performance of alternative production systems with the performance of the predominant conventional production system, i.e., backgrounding and finishing steers in LR. More detailed information of the livestock strategies is provided in Supplementary Material S2.

3. Outcomes of the 'Palo a Pique' Long-Term Experiment

3.1. Some Key Results

After 8 years of running the experiment (1995–2003), Terra et al. [24] reported a significant SOC reduction of 17% in the 0–15 cm depth under the continuous crop (CC) relative to the other rotations containing a high proportion of perennial pastures in their cycles (LR and PP) (Figure 4). The authors suggested that despite using no-till CC, SOC decreased relative to its original conditions, while pastures had the ability to recover SOC that had been lost during the cropping phase [18]. Soil organic carbon reduction in CC was due to a negative carbon (C) balance generated by biomass extraction by grazing cattle, while the higher content of SOC in pasture-based rotations was related to the greater biomass partitioned to the root systems compared to CC [24]. Recently, evaluating and modeling the four rotations using sophisticated algorithms suggested that perennial pastures underpin soil C and nitrogen (N) cycling in crop rotations by maintaining soil C closer to saturation [29].

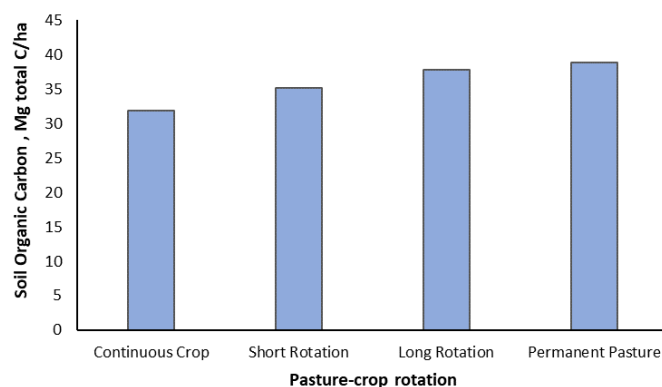


Figure 4. Crop–livestock rotation impact on soil organic carbon (SOC, 0–15 cm depth) from the ‘Palo a Pique’ long-term experiment (1995–2003). Content of SOC in continuous cropping was significantly lower than SOC in the other rotations. Adapted from Terra et al. [18].

From the livestock production standpoint, average liveweight gains (\pm standard deviation) for the first four years of the experiment ranged from 338 ± 103 to 527 ± 61 kg/ha per year, whilst average forage production ranged between 7.9 and 10.2 t DM/ha per year, allowing an animal carrying capacity between 480 and 951 kg LW/ha per year (Figure 5) ([14]. These KPI values are between two and four times greater than those recorded in traditional livestock production systems in Uruguay in terms of liveweight gain production, pasture production, and stocking rate (105 kg LW/ha, 4.4 t DM/ha, and 300 kg LW/ha per year, respectively) [30]. Production intensification is one way to reduce carbon footprint per animal and per hectare [31]. In Uruguay, Picasso et al. [32] found that for every 10 kg increase in productivity (kg LW/ha per year), the carbon footprint decreases by 1.2 kg CO₂e/kg LW and 36 kg CO₂e/ha.

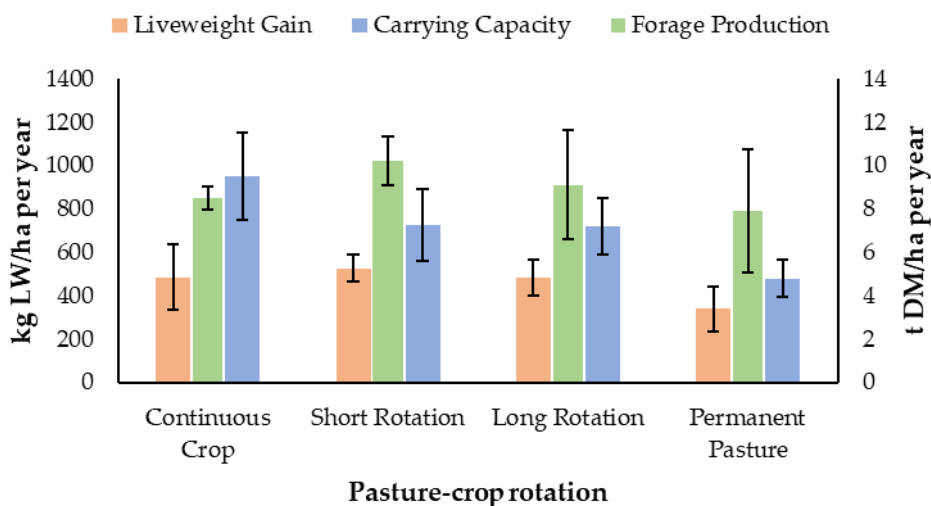


Figure 5. Forage production, liveweight gain, and carrying capacity of four different pasture–crop rotations (‘Palo a Pique’ long-term experiment, 1996–1999). Adapted from Terra and García-Préchac [14].

In 2015, after 10 years of running Phase II of the LTE, Terra and Macedo [33] reported significant SOC differences between grain-and forage-based rotations (GR and FR, respectively) (Figure 6). In CC, FR had 12% less SOC (0–15 cm depth) than GR. When crops were harvested only for grain, i.e., leaving undisturbed residues in situ, SOC levels indicated that GR with no-till technology would be more sustainable than FR, which removes a higher proportion of aerial biomass by direct livestock grazing [12,34]. However, regardless of the lower amount of residue left under grazing conditions, Moraes et al. [35] reported that grazing stimulates the production of tillers and roots by shoot renewal.

Therefore, considering the sum of the herbage mass and herbage growth during the grazing period, there is a greater extent of dry matter accumulation in moderately grazed areas. Additionally, there are several positive effects of integrated crop–livestock systems compared with continuous cropping, including greater soil density and aggregation, and increased soil microbial mass and diversity [35,36]. Overall, no SOC differences were found between SR and LR, but they had 8.4% lower SOC than PP, both in GR and FR. Results suggested that even under no-till and pasture rotations, cropping systems reduced SOC compared with PP, and that a pasture cycle is critical to mitigate SOC losses during cropping [33]. Information about crop productivity has been partially published [37,38]. No differences were found in crop yield between the different crop–livestock rotations in the period 2005–2016, averaging (\pm standard deviation) 2499 ± 888 , 4871 ± 1758 , 2771 ± 1158 , and 1569 ± 479 kg/ha for soybean, sorghum, wheat, and oat, respectively, across rotations.

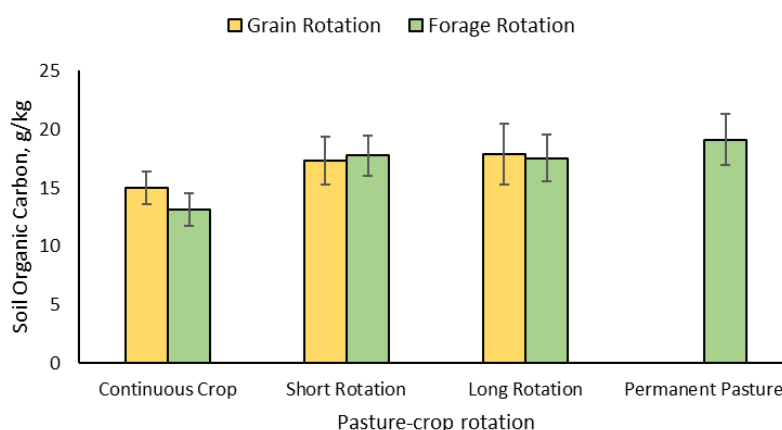


Figure 6. Pasture–crop rotation impact on soil organic carbon (mean \pm s.d; 0–15 cm depth) from the ‘Palo a Pique’ long-term experiment (1995–2015). Adapted from Terra and Macedo [33].

3.2. Policy Implications

There are broader practical outcomes and impacts of the LTE when they influence the design of policy strategies [39]. While the ‘Palo a Pique’ experiment was designed to address agricultural system sustainability in the long term, various short-term trials nested within the context of the LTE were conducted to explain some of the results obtained or to answer relevant short-term questions as the LTE progressed. These studies contributed greatly to a detailed understanding of soil erosion and acidity, nutrient dynamics, soil compaction, pasture renewal, weed control, and livestock impacts on the subsequent crop. A comprehensive description of these studies for the early years is provided by Terra and García-Préchac [14]. A full list of extension publications and articles in technical bulletins is provided in Supplementary material S3. As an interesting example, it is useful to highlight an experiment, mirroring the different rotations tested in the ‘Palo a Pique’ LTE, that was implemented in small runoff plots to measure the soil erosion associated with precipitation. This allowed a more precise estimate of soil erosion coefficients considering the variation in the amount of water held in the soil after natural rainfall events [40,41].

Taken together, short and long-term results from the ‘Palo a Pique’ experiment have provided vital information to estimate soil erosion under the climatic and soil conditions in eastern Uruguay. This local data, along with information from other national and international sources, was considered by official authorities from the Ministry of Livestock, Agriculture and Fishery to develop the mandatory Soil Use and Management Plan. According to Uruguayan official regulations, each crop farmer must present a land use and management plan to the official authorities showing that the rotation under consideration would generate an average annual erosion below the level officially established. The soil loss estimation is made with the Revised Universal Soil Loss Equation (or RUSLE) [41,42] which was validated in Uruguay with data that included the ones obtained in the Palo a Pique runoff plots, mentioned before.

Data from the ‘Palo a Pique’ LTE (33°15′54.4″ S 54°29′28.1″ W) was combined with scientific data from other geographic regions of Uruguay to account for inherent agro-climatic variability, e.g., with the oldest LTE in Uruguay initiated in 1963 at INIA La Estanzuela (34°20′ S, 57°41′ W) to evaluate seven pasture–crop systems [17]. As a result, authorities suggested the correction of the original RUSLE equation because it overestimated the value of soil erosion by 35% in Uruguayan agricultural soils, influenced by climate, species composition, edaphic conditions, and tillage practices [40]. This is a clear example of how results derived from the ‘Palo a Pique’ LTE contributed to influence policy makers.

The new orientation of the ‘Palo a Pique’ LTE towards livestock intensification will create a scenario of trade-offs between increasing animal production and environmental impact. Some of the concerns are the potential impact on water-related ecosystem services [43], greenhouse gas emissions [30], environmental footprint, nutrient imbalances and biodiversity [32]. The generation of system–science-based data from LTE mirroring commercial enterprises will allow the identification of key areas that need to be addressed in policy development to ensure that biological and economic productivity is maintained in agroecosystems without compromising ecological indicators. To achieve this objective, it is imperative to improve precision in measuring KPIs in a more location-specific context to provide policy makers with evidence-based data concerning the environmental impact of crop–livestock production systems. This requires a significant investment into applied and large scale research, something that is not always compatible with scientific rigor [44]. However, LTE research platforms provide opportunities not only for new research topics, but also for more detailed, controlled, and randomized studies to uncover the cause–effect mechanisms behind long-term trends [39].

4. New Challenges of the ‘Palo a Pique’ Long-Term Experiment

4.1. New Hypothesis and Approach

The original research question of the ‘Palo a Pique’ LTE in 1994 was: “Can no-till technology and pasture–crop rotations allow sustainable agricultural intensification in marginal soils in eastern Uruguay?” Twenty-five years later, the new research question is: “Can different pasture–crop rotations match different livestock strategies to allow sustainable ruminant livestock intensification?”. Several key changes have occurred in commercial production systems that lies behind the transition in the research question, from agriculture to livestock. These include: (i) the conversion of marginal crop areas to pasture production [45], (ii) increased use of crops for livestock grazing (i.e., cover crops) [46], (iii) increased use of crops in animal feed (i.e., high moisture sorghum grain) [43], (iv) stricter regulations and controls for intensive crop rotations [42], and (v) greater variability in market niches for livestock production (i.e., European Union high-quality beef quota) [47]. Moreover, from the research standpoint, there was a need for new challenges to revitalize and keep the LTE attractive, but not at the expense of its long-term viability. Flexibility is a desired component of any LTE, allowing the sporadic introduction of changes or allowing hypothesis re-orientation to address any global and local demands that may arise over time.

With animal protein set to remain a significant part of food demand, it is necessary to pursue sustainable livestock intensification and devise strategies to keep animals in ways that work best for farmers, communities and the planet [22,48]. General approaches to pursue sustainable livestock intensification in the new design of the ‘Palo a Pique’ LTE include: (i) shortening the production cycle, (ii) diversifying animal categories, (iii) adapting system management to match rotation and livestock potential, (iv) adding the ‘concept of strategic use’ of natural grasslands as a support area for improved pastures, (v) increasing LW gain and final LW, and (vi) managing trade-offs to reduce negative externalities. This last point is directly aimed at minimizing adverse impacts of livestock or agriculture on climate change. For example, CC has the lowest proportion of pastures in the rotation and, therefore, less potential for atmospheric C sequestration, but it is compensated with a shorter livestock strategy (12 months) and a more efficient animal category (calves), with lower greenhouse gas (GHG) emissions. Conversely, LR has the longest livestock strategy (emitting more GHGs), but is

compensated with a higher proportion of pastures in the rotation, capturing more C. Therefore, the interactions of integrated crop/livestock systems might be more relevant than rotations or livestock strategy options alone. This falls under the concept of ‘carbon neutral beef’ derived from integrated systems with biological components able to capture significant amounts of C from the atmosphere as pastures or forestry [49,50].

The current core objective of the ‘Palo a Pique’ LTE is to evaluate four ways of producing 400 kg LW/ha per year based on pasture–crop rotations under no-till technology, that is economically, environmentally and operationally viable. The LTE is now more complex, as it includes a second factor (livestock strategy) in addition to the pasture–crop rotation, but the original comparison of the different rotations under no-till technology is still present. While careful design and planning is critical to all systems, unforeseen issues that require quick decision making can arise. Short-term decisions related to livestock and pasture management (stocking rate, supplementation level, etc.) are recognized as intrinsic properties of each system, dependent on the different animal categories, variation in the grazing area and pasture productivity. It was decided that each system must be managed to express its potential and reach the desired level of production (400 kg LW/ha per year). From a methodological standpoint, a system that acts as a ‘negative control’ is not desirable, conversely, the aim is for four systems running at their maximum performance. Hence, the different systems are permitted to evolve along their own trajectories, as long as the main contrast remains the same, i.e., the four pasture–crop rotations with no-till technology.

4.2. Sustainability Metrics

Key performance indicators provide a practical assessment of the sustainability of an animal production system, and for those KPI levels to be maintained or increased over time there must be a match between the livestock strategy, pastures, climate and system management. Assuming the first three conditions are met, management becomes important [51]. We expect that the four systems will tend to be stabilized in terms of the short-term decisions after two production cycles.

Supplementary Material S4 shows the evolution of the basic set of metrics through the different phases of the ‘Palo a Pique’ LTE. The present phase resumes the measurement of some indicators that had been discontinued and add new indicators, especially at the pasture, animal, and system levels. This is in accordance with the new twist of the LTE: revitalize the livestock, economic and environmental dimension, while keeping stable the robust metrics in soil and crops. To address such complexities, combining high-resolution primary field data with modeling to provide whole-farm simulations is an appropriate approach for evaluating the environmental impact of different production systems [52,53]. In this way, the original pasture–crop rotations at the ‘Palo a Pique’ LTE have become a platform for new studies that model system effects on the environment using life cycle assessment (LCA) methodology [54]. Studies employing LCA approaches estimate pollution–production ratios as their primary outputs (i.e., kg CO₂e per unit of food produced), where farming systems that have low scores are determined to be more desirable, although nutrient quality and the entire supply chain must also be considered [53,55,56]. Table 1 shows a simplified prediction of environmental KPIs in the four systems of the ‘Palo a Pique’ LTE recommended by Kanter et al. [31] for developing transformation pathways in Uruguay’s beef sector. Assuming all systems reach the target of production (400 kg LW/ha/year), rotations with higher proportion of pastures (greater C sequestration), more legumes (less N run-off and leaching) and greater diversity of plant species would be more suitable to achieve sustainable development goals.

The biological diversity found in mixed crop–livestock systems results in more efficient nutrient cycling than in specialized crop or livestock production systems since nutrients in forage crops and perennial pastures consumed by livestock are returned to the land through manure deposition, enhancing soil fertility and C sequestration [57,58]. This fits well within the circular bioeconomy concept as a strategic approach towards system sustainability [59]. In the ‘Palo a Pique’ LTE, the pasture-based rotational grazing applied on each system implies homogeneous and natural ‘circularization’ of animal

manure within the boundaries of each system. Moreover, the sorghum grain and hay produced during the crop phase of each rotation is destined to feed the animals belonging to each rotation, promoting not only the circularization of nutrients, but also food self-sufficiency (i.e., reducing the amount of external inputs).

Table 1. Predicted environmental impact of the four systems in the ‘Palo a Pique’ long-term experiment, focused on carbon sequestration, nitrogen pollution and biodiversity (adapted from Kanter et al., 2016).

Issue	Metrics	Pasture–Crop Rotation			
		LR	SR	CC	PP
Animal production	Kg LW/ha/year	++++	++++	++++	++++
Carbon footprint	% pastures	+++	++	+	++++
Nitrogen	% legume-based pastures	+++	++	+	+
Biodiversity	N° of species (richness)	++++	+++	++	+

LR: Long Rotation; SR: Short Rotation; CC: Continuous Crop; PP: Permanent Improved Pasture; ++++: most favorable environmental impact; +: less favorable environmental impact.

5. Conclusions

Based on the results obtained from Phases I and II of the ‘Palo a Pique’ LTE, pasture–crop rotations with no-till are sustainable systems under the Uruguayan productive conditions, even when most of the aerial biomass is harvested and exported by direct grazing. Data have shown the importance of no-till technology, crop diversification, biomass residuals returned to the soil, and the inclusion of perennial grasses and legumes, as key factors to assure the sustainability of pasture–crop rotations in soils with high risk of erosion.

Cropping and livestock integration are expected to continue with increased global demand for protein sources, much of which will originate in the developing world. Thus, increased productivity in livestock and crop production will become critically important not only to produce food, but also to keep farmers in agricultural regions. In a world where there is an increasing demand for meat, the solution cannot be to limit production (i.e., through meat taxes or policies based on perceptions), but to find a way to guarantee an adequate food supply, seeking convergence between the environmental, economic, and social dimensions. The current design of the ‘Palo a Pique’ LTE has rationalized the role of ruminants converting grass and by-products of little or no value for human food into high-quality protein, balancing food production for humans and the production of feed for animals in marginal soils for agriculture, where continuous cropping is unsustainable due to SOC loss.

In the context of the continuing debate concerning the role of ruminants in land use, climate change, and food security, the ‘Palo a Pique’ LTE along with other LTEs of the Global Farm Platform (www.globalfarmplatform.org) initiative offers new opportunities for international collaborative research to develop common sustainability metrics that provide a detailed understanding of how ruminant-based systems work, and how they can be managed for sustainable intensification at the global scale.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4395/10/3/441/s1>, Table S1: General characteristics of the ‘Palo a Pique’ long-term experiment, Table S2: Detailed description of the new livestock strategies for each pasture-crop rotation (2019–present), Table S3: List of publications from the ‘Palo a Pique’ long-term experiment (1995–present) (Sorted by year of publication), Table S4: Evolution of the basic set of metrics collected in the ‘Palo a Pique’ long term experiment (1995–2019). Superscript numbers mean measurement frequency: 1 Once per year; 2 Once per season, 3 Once per month or less, 4 Once per month, except carcass data (every time animals are sent to slaughter).

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