**Introduction**

This work addresses the sustainable intensification of production systems through the analysis of four systems that combine agriculture and livestock with varying levels of soil use intensification. We evaluated their economic outcomes, environmental impact (i.e., emission profiles, contribution of each process, and partial carbon footprint), and contributions to food security using data from a long-term experiment.

**Material and Methods**

The study evaluated four crop-livestock systems in Uruguay, with temporal and spatial combinations of land use (Table 1). The continuous cropping system (CC, 12 ha) involves reseeding two crops per year without rotating with pastures but includes an external 6 ha area of permanent pasture with tall fescue, birdsfoot trefoil, and white clover, reseeded every five years for continuous growth. The short rotation system (SR, 24 ha) alternates two years of crops, similar to the CC system, with two years of grass-legume pastures, including Yorkshire fog and Italian ryegrass with red clover. The long rotation system (LR, 36 ha) alternates two years of crops, as in the CC and SR systems, with four years of pastures composed of tall fescue, birdsfoot trefoil, and white clover. The forage rotation system (FR, 24 ha) is reseeded with tall fescue and does not include crop rotations. Each pasture-crop rotation (CC, SR, and LR) is divided into two areas: one for grain production, planted with oats, wheat, soybean, and sorghum; and one for grazing, where Italian ryegrass and oats are planted in winter, and sorghum and moha are grown in summer.

In the CC, SR, and LR systems, animals are introduced to their paddocks from April to May and remain for one year (for rearing) or until reaching slaughter weight (for finishing). In the FR system, animals are introduced from November to December annually. In CC, the objective was to rear male calves for one year. In SR, the objective was to rear heifers, complemented by finishing culled cows during May and September. In LR, the objective was to rear male calves and finish steers over 18 months. FR begins at the end of spring (Nov-Dec) with yearling steers instead of weaned calves. The objective of the livestock strategy in FR was to produce a finished steer ready for slaughter in 12-15 months. British early-maturing beef cattle were used in the four systems (Hereford, Aberdeen Angus, and Hereford-Angus cross).

**Table 1.** Cropping and pasture sequences of the four pasture-crop rotations at the ‘Palo a Pique’ long term experiment.



Note: Yellow and green areas represent crop and pasture phases, respectively. P: pasture, followed by pasture age (i.e.: P2: second-year pasture). All pastures, including those following the grain/hay crop phase, were available for grazing.

Production data (grain and livestock) was obtained from Pereyra-Goday et al. (2022). Carbon footprints were calculated following Life Cycle Assessment (LCA) methodologies, as reported in Pereyra-Goday et al. (2024). Nitrogen use efficiency (NUE) was calculated as nitrogen in food outputs relative to total nitrogen inputs, as reported in Pereyra-Goday (2024). Economic data was collected on input costs and revenues from grain and livestock sales based on the physical parameters for tree cycles (2019-2022), as reported by Pereyra-Goday et al. (2022). We evaluated the contribution to food security through the production of human-edible protein (HEP) and human-edible energy (HEE), using the methodology proposed by Mosnier et al. (2021). Lastly, soil erosion was estimated using the Universal Soil Loss Equation (USLE-RUSLE) model (software Erosión 6.0, MGAP, Uruguay).

**Results and Discussion**

A summary of the main sustainability indicators calculated are shown in Table 2. The grey cells indicate that no statistical analysis was permitted due to the lack of replicates, green cells mean high/desirable values, red cells mean low/non-desired values, and yellow cells mean intermediate values. Systems with integrated crop-livestock components, especially those with longer pasture phases (LR), provide greater environmental benefits by reducing soil erosion and carbon emissions. These systems also enhance NUE due to biological nitrogen fixation from legumes. However, the CC system, with its intensive cropping strategy, delivers higher short-term economic returns and food production but poses long-term sustainability risks due to higher soil losses and emissions. Pasture-based systems (FR and LR) offer valuable ecosystem services, including nutrient recycling, carbon sequestration, and biodiversity conservation. Although they yield lower human-edible protein and energy, they avoid direct competition with human food supply and contribute to a more sustainable agricultural model. The systems combining pasture and cropping (SR and LR) yielded the highest economic returns due to the diversification of income sources. The CC system showed high production costs but delivered higher returns in favourable years. Systems with a greater focus on pasture, such as FR, exhibited lower production variability but also lower overall productivity.

**Table 2. Main indicators calculated for the four systems (“\*” there was not harvest, “-“ does not apply).**

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**1Pereyra-Goday et al (2022); 2Pereyra-Goday et al (2024); 3Pereyra-Goday et al (2025);4This study**

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