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The wide (un)sustainability ranges of agroexporting territories: Insights from Uruguay

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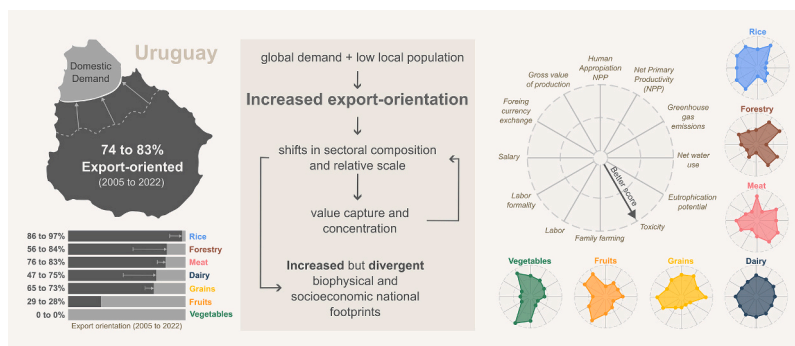
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HIGHLIGHTS

- Export-oriented land use in Uruguay grew from 74% to 83% in two decades.
- Higher economic output is linked to contrasting environmental footprints across sectors.
- Alternative sectoral arrangements yield divergent sustainability outcomes.
- Rising concentration in few sectors and actors poses governance challenges.

GRAPHICAL ABSTRACT



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ABSTRACT

Agroexporting countries play a central role in global food and biomaterials supply, yet their strong external orientation influences the way economic, social, and environmental tensions are navigated at the national scale. Here, we examined how global trade shapes sustainability outcomes in Uruguay through an integrated assessment of key producing sectors: meat, dairy, grains, rice, fruits, vegetables and forestry. We quantified sectoral size, market orientation, multidimensional performance, and the value distribution across farms. We showed that

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export-oriented land use grew from 74% to 83% between 2005 and 2022, reallocating >1.5 Mha (9% of land) toward external markets. Over the same period, shifts in sectoral composition increased national socioeconomic output. However, sectors differed sharply in their intrinsic footprints (e.g., up to 19-fold differences in water use and 16-fold in pesticide use) and in the biophysical and social pressures associated with generating economic outcomes. Per unit of value generated, pesticide use across export-oriented sectors ranged from 0.43 to 5.10 g per USD, while water use ranged from -1.39 to 7.35 m^3 per USD, implying that compositional shifts toward higher economic output can produce substantial yet contrasting sustainability outcomes. Concentration was marked, with large farms (<0.5% of farms) capturing 28% of gross production value, mainly fueled by forestry and grains. Together, these results confirm that both the extent of territory exposed to global markets and the sectors occupying that space critically shape aggregated footprints. Which sectors occupy the export-oriented land and who captures value ultimately determine national trajectories, making outcomes contingent and politically contested.

1. Introduction

The ways in which humans produce food and other land-based products are increasingly recognized as a key pressure on Earth system processes and planetary boundaries (Rockström et al., 2009; Wood et al., 2022; Wu et al., 2024). Global demand for these primary materials continues to grow, driven by a still-expanding population and changing consumption patterns toward resource-intensive products, especially animal-based foods, packaging materials, and industrial crops (Searchinger et al., 2019; Oberle et al., 2019). This has resulted in the replacement of vast natural ecosystems and the intensification of others already transformed, positioning land use as a major global threat while simultaneously generating significant environmental and social impacts at a local scale (Ellis et al., 2010; Kastner et al., 2021; Paruelo et al., 2024).

Due to global trade, the intensity of these transformations has been highly uneven across the world (Liu et al., 2013; Meyfroidt et al., 2024). Territories rich in natural resources, such as parts of Latin America, Southeast Asia, and Sub-Saharan Africa, have experienced particularly deep changes over the past decades, often linked to the expansion of export-oriented production systems (Graziano-Ceddia, 2019; Meyfroidt et al., 2024). Latin America in particular has played a long and pivotal role in the history of agroexports and global agri-food supply (Baraibar-Norberg, 2020; Infante-Amate et al., 2022), and has intensified dramatically alongside the unprecedented expansion of global trade (Oberle et al., 2019). This market integration process has led to a growing spatial decoupling between production and consumption, allowing distant territories to strongly influence land use and production decisions (Aguiar et al., 2020; Liu et al., 2021; Schwarzmüller and Kastner, 2022). While this has contributed to global food security and may, in some contexts, relieve pressure in resource-constrained agroecosystems (D'Odorico et al., 2014; Beyer et al., 2022), it also exacerbates pressures for agroexporting countries (Kastner et al., 2021; Liu et al., 2021).

Agroexporting countries can be broadly defined as those where the production of land-based products (i.e., food, fibers, biomass, etc.) exceeds domestic demand by a wide margin and constitutes a dominant share of the national export basket, positioning them in a structural role within global trade (Baer-Nawrocka and Sadowski, 2019; Baraibar-Norberg, 2020; Hidalgo, 2023). In these economies, land-based activities play a central role not only in employment and foreign exchange generation but also in shaping fiscal policy, macroeconomic stability and development strategies (Ayompe et al., 2021; Conroy et al., 2024). As a result, sustainability agendas of agroexporting countries are strongly conditioned by this structural dependence on external markets and trade priorities (Morris et al., 2020; Jobbágy et al., 2021).

At the same time, how this external dependence translates into land-use change, sectoral expansion, and sustainability outcomes is mediated by domestic political, institutional, and economic factors (Baraibar-Norberg, 2020; Clapp et al., 2025). Efforts to enhance competitiveness may conflict with social inclusion or environmental conservation, while attempts to diversify productive structures are often constrained by

entrenched positions within global production networks (Hidalgo, 2023; Wu et al., 2024). This combination of external pressures and internal constraints creates persistent tensions between economic, social, and environmental objectives, making sustainability a contested and structurally conditioned outcome rather than a straightforward policy choice (Martin et al., 2024; Sumberg et al., 2023).

Despite substantial research on international trade, land-use change, and sectoral sustainability, it remains poorly understood how agroexporting countries translate the pursuit of increased economic value into national sustainability outcomes (Jobbágy and Sala, 2014). In practice, this pursuit unfolds as different sectors compete for a shared territorial and productive space, responding unevenly to external and domestic market signals as well as to locally defined rules and incentives. Consequently, we lack an integrated understanding of how changes in sectoral composition, arising from shifts in production scale and market orientation, translate into aggregate national sustainability outcomes and interact with economic concentration and power, giving rise to a wide spectrum of possible national sustainability trajectories, which we refer to here as (un)sustainability ranges (Bridge, 2008; Gudynas, 2013; Clapp et al., 2025).

Addressing this gap requires an approach that integrates insights from land-system science, telecoupling, and political economy. Land-system and planetary boundary frameworks have been instrumental in identifying biophysical constraints on production systems (Rockström et al., 2009; Kastner et al., 2021; Meyfroidt et al., 2024), yet they rarely account for why specific sectors expand or contract within national territories. Telecoupling perspectives, while illuminating global interconnections, often treat exporting regions as structurally homogeneous and have paid limited attention to domestic institutional configurations (D'Odorico et al., 2014; Liu et al., 2021; Baraibar-Norberg, 2020). Part of this analytical limitation also relates to the scale at which sustainability dynamics are typically examined. Studies conducted at micro scales often provide detailed insights but remain confined to individual sectors or farms (Bridge, 2008; Baylis et al., 2021; Castillo-Díaz et al., 2024), while macro-level assessments tend to privilege single dimensions, thereby obscuring cross-sectoral contrasts (Balogh and Jámor, 2020; Kastner et al., 2021). Bringing these perspectives together enables a meso-scale analytical framework capable of linking sectoral dynamics, market orientation, and biophysical pressures within a shared territorial context. Such integration facilitates the identification of structural asymmetries and sustainability trade-offs that are often obscured in single-sector or purely macro-level analyses.

Uruguay provides a particularly suitable case to operationalize this approach. As a strongly export-oriented economy where land-based activities dominate both the productive structure and the export basket, Uruguay reflects the dilemmas of many agroexporting countries but in a more concentrated form. It has a notably low population density ($19.5 \text{ inhabitants km}^{-2}$), which is even more extreme in rural areas given its high degree of urbanization. The land-based sector, including related industries, represents a substantial share of national gross domestic product and accounts for the majority of goods exports. Interestingly, over 60% of its land is still covered by native grasslands, a

biome that elsewhere has already been subject to massive conversion to agriculture (Ellis et al., 2010; Schwarzmüller and Kastner, 2022). Lacking other major extractive sectors such as mining or fossil fuel extraction, Uruguay allows a direct examination of the tensions between export-driven growth and the sustainability of land-based systems. Its productive diversity, ranging from large-scale industrial crops and forestry to extensive livestock and smaller-scale horticulture, within a relatively uniform environmental setting originally dominated by temperate humid grasslands, provides a unique opportunity to compare sectors with differing practices, actors, and impacts under a shared biophysical context and within a single national framework.

By placing Uruguay's main land-based sectors side by side under a common analytical lens, we move beyond descriptive accounts and formulate testable hypotheses on how sectoral expansion, intensification, and concentration shape national sustainability outcomes in agroexporting contexts. Building on this comparative, cross-sectoral perspective, we hypothesize that long-standing agroexporting countries with low demographic growth, as is the case for Uruguay and most South American nations during the 21st century (Morris et al., 2020), experience a progressive intensification of their global agroexporting role and its associated local socio-environmental footprint. Specifically, we hypothesize that during the last two decades:

- (i) Productivity gains and demographic stagnation, combined with deepening integration into global commodity markets, have led to a differential expansion of export-oriented sectors, resulting in a reallocation of land toward activities with higher economic output per unit area.
- (ii) Emerging agroexporting sectors have achieved higher economic output through more intensive biophysical and human inputs, resulting in deeper environmental footprints in terms of nutrient use, water consumption, and chemical inputs.
- (iii) Sectors characterized by higher capital intensity and economies of scale have been structurally better positioned to capture global demand, generating reinforcing feedbacks between sectoral expansion and concentration of value, thereby increasing the concentration of economic flows among a limited set of actors.

2. Materials and methods

We assessed Uruguay's main land-based production sectors (meat, dairy, grains, rice, fruits, vegetables, and forestry), which together account for 94% of continental land and 95% of agricultural gross production value, at the national level and using a combination of quantitative and comparative approaches.

To examine changes in Uruguay's agroexporting space over time (Hypothesis 1), we analyzed sectoral trajectories in area, productivity, and market orientation between 2005 and 2022. We quantified how total production was partitioned between exports and domestic use, and how domestic demand was met through local production *versus* imports, using a material-balance framework that integrated production statistics and trade flows.

Current sectoral performance was characterized through a multidimensional comparative assessment (Hypothesis 2), based on twelve biophysical and socioeconomic indicators derived from multiple national sources (see below). This assessment was complemented by a counterfactual backcasting exercise, in which current observed national outcomes were compared against a baseline sectoral configuration defined at the beginning of the study period.

Finally, to assess patterns of economic concentration across and within sectors (Hypothesis 3), we disaggregated sectoral gross production value across economic farm-size classes using official farm-size statistics and complementary sector-specific sources.

We assessed Uruguay's main land-based production sectors (meat, dairy, grains, rice, fruits, vegetables, and forestry), which together account for 94% of continental land and 95% of agricultural gross

production value, at the national level and using a combination of quantitative and comparative approaches. We quantified sectoral size, market orientation, sectoral multidimensional performance, and the value distribution across farms. All these analyses drew on a combination of official statistics, semi-public datasets, and complementary technical reports Supplementary Material 1. Production and trade data were primarily obtained from the Agricultural Statistical Yearbooks of the Ministry of Livestock, Agriculture, and Fisheries (DIEA-MGAP), complemented by datasets from the Office of Agricultural Planning and Policy (OPYPA), the Directorate for Rural Development (DGDR), Uruguay XXI, and the Metropolitan Agrofood Unit (UAM). When official data were unavailable or insufficiently detailed, we supplemented them with sectoral reports, published scientific literature, and expert consultations. While individual sources vary in coverage and resolution, their combined use allowed us to construct a coherent and sector-comparable dataset underpinning all analyses.

2.1. Selection of sectors

Sectors were defined primarily by the identity of the final product (e.g., milk, grains, wood) rather than by uniformity of production practices, which can vary substantially within each category.

Each sector includes multiple products and reflects considerable internal diversity in production systems, farm scales, and geographic distribution. For example, the fruit sector covers citrus, vineyards, and pome fruits (detailed in Supplementary Material 1A). The meat sector is restricted to ruminant production (bovine and ovine), which relies directly on land ecosystems through grazing, and therefore excludes poultry and swine systems, which are intensive operations largely decoupled from direct land use. While treating meat or grains as single sectors necessarily obscures internal heterogeneity, this aggregation reflects the structure of available data and responds to the need for cross-sector comparability.

Although farms in Uruguay often combine sectors either spatially (e.g., livestock and forestry on the same land) or temporally (e.g., rice-livestock rotations), our focus was not on farms as units but on sectors as analytical categories. This sectoral framing enabled systematic comparison across domains, while acknowledging the underlying diversity of products, production scales, and territorial specificities. The analysis concentrated on the primary production stage, where the most direct interactions with land and ecosystems occur.

2.2. Market orientation and size distortion

To assess how the orientation of production shifted toward external markets at the national level and within sectors, we developed a material-balance framework reconciling national production, imports, and exports. All flows were converted into raw material equivalents to ensure comparability across sectors and processing levels, with conversion coefficients detailed in Supplementary Material 1B. Market orientation was calculated by relating sectoral exports to total production and evaluated using two contrasting multi-year windows (2005–2007 and 2020–2022). This window-based approach was used to capture structural changes in market orientation over time, rather than year-to-year variability. By linking sectoral market orientation with land cover, we estimated how much of the national territory was effectively allocated to domestic consumption *versus* external demand. Sectoral size distortion was estimated by relating apparent domestic consumption (i.e., local demand) to total production.

2.3. Comparative multidimensional assessment

We selected twelve indicators spanning key biophysical and socioeconomic functions of land-based production sectors in Uruguay, aiming to balance policy relevance, empirical robustness, and cross-sector comparability. Indicators were chosen to capture comparable

functions across sectors, such as pressures on biophysical cycles, labor and value generation, and degrees of territorial embeddedness, rather than to compare specific technologies or management practices. The purpose of this comparative assessment was not to characterize the full internal variability of each sector, but to capture their dominant structural configurations. Indicators therefore reflect typical or modal characteristics that shape aggregate flows of land, resources, value, and labor at the national level across sectors. As such, cross-sectoral comparisons reflect general sectoral patterns rather than the full range of within-sector variability, and should be interpreted accordingly. Within this scope, the approach is appropriate for addressing our research question, which focuses on how sectoral composition and relative scale translate into national sustainability outcomes.

Although important dimensions such as biodiversity, soil condition, gender equity, employment seasonality, and vulnerability to market shocks were not included, largely due to data limitations and the need to maintain balance across domains, the selected indicators provide a robust basis for capturing dominant sectoral contrasts at the national level.

To explore relationships among indicators, Spearman's rank correlation and principal component analysis were applied to assess the overall pattern of sectoral impacts. Detailed descriptions of each indicator, data sources, and estimation procedures are provided below:

2.3.1. Greenhouse gas emissions

Estimated annual emissions (kg CO₂-eq ha⁻¹ yr⁻¹) per sector, based on Uruguay's national greenhouse gases inventory 1990–2020. Emissions from sources like enteric fermentation, manure management, biomass burning, land-use change, urea and fertilizer application, feces, and residues were originally reported as CO₂, CH₄, or N₂O, then converted to CO₂ equivalents using global warming potentials of 28 for CH₄ and 265 for N₂O, with CO₂ as reference.

2.3.2. Net water use

Estimated annual net water use (m³ ha⁻¹ yr⁻¹) per sector, including both green and blue water (Falkenmark and Rockström, 2004). This indicator combines three main components: consumptive irrigation water use (blue water), consumptive water use for other purposes (blue water; e.g., animal consumption, washing in dairy-facilities, packing of fruits and vegetables), and changes in evapotranspiration relative to natural vegetation (green water). Detailed methods for calculating irrigation water use, evapotranspiration changes, and other water uses are provided in Supplementary Material 1C.

2.3.3. Eutrophication potential

Estimated annual nutrient input pressure per hectare (kg ha⁻¹ yr⁻¹) expressed as macronutrients (nitrogen, phosphorus, and potassium). This indicator includes inputs in the form of chemical fertilizers, organic amendments, imported animal feed, and livestock movements. Details of these estimations are provided in Supplementary Material 1D.

2.3.4. Toxicity

Estimated pesticide use (g active ingredient ha⁻¹ yr⁻¹), including insecticides, herbicides, and fungicides, based on modal management practices for each dominant crop and land cover within each sector. Modal practices were defined based on expert consultation and typical technical recommendations, as detailed in Supplementary Material 1E.

2.3.5. Net primary productivity

Estimated annual net primary productivity (kg dry matter ha⁻¹ yr⁻¹), based on the composition of land covers within each sector and their associated above- and below-ground biomass productivity. This indicator reflects the overall transformation of ecosystem processes into biomass. Values were obtained or estimated from published sources, as detailed in Supplementary Material 1F.

2.3.6. Human appropriation of net primary productivity

Proportion of net primary productivity (%) harvested or removed from the system. Estimates are based on biomass extraction values for each sector, as detailed in Supplementary Material 1F.

2.3.7. Family farming

Share of family farming units (%) within each production sector, based on official records from Uruguay's Ministry of Livestock, Agriculture, and Fisheries. This indicator relates to the territorial rootedness of production, reflecting the direct connection of people with the land, local culture, and community life.

2.3.8. Labor

Number of employed people (full-time equivalents) per 100 ha, by sector. Data were obtained from internal reports of Uruguay's Ministry of Livestock, Agriculture, and Fisheries (Ackermann and Cortelezzi, 2018). This includes salaried workers, self-employed, and unpaid family labor.

2.3.9. Labor formality

Share employment under formal labor conditions (%). Unpaid family labor was classified as informal. Data were obtained from internal reports of Uruguay's Ministry of Livestock, Agriculture, and Fisheries (Ackermann and Cortelezzi, 2018).

2.3.10. Salary

Average hourly wage (USD hour⁻¹) per sector. Data were obtained from internal reports of Uruguay's Ministry of Livestock, Agriculture, and Fisheries (Ackermann and Cortelezzi, 2018) and adjusted to 2022 values using the national Consumer Price Index.

2.3.11. Net foreign currency exchange

Estimated net foreign currency generation per hectare (USD ha⁻¹ yr⁻¹), calculated as the difference between total exports and associated imports for each sector. Export and import data were obtained from Uruguay's agricultural statistical yearbooks (MGAP-DIEA). Associated imports include sectoral products not produced domestically (e.g., grains imported) and essential inputs (i.e., fertilizers and pesticides). They were valued using sector-specific volumes and average prices over 2020–2022. Methodological details are provided in Supplementary Material 1G.

2.3.12. Gross production value

Estimated gross production value per hectare at the farm-gate level (USD ha⁻¹ yr⁻¹), based on reported production volumes per sector from Uruguay's agricultural statistical yearbooks (MGAP-DIEA) and average product prices over 2020–2022. Prices were adjusted to reflect those received by producers, excluding intermediary margins and typical transport costs. Methodological details are provided in Supplementary Material 1H.

2.4. Farm-size and distribution of gross production value

Disaggregating production by farm size provides a basis to assess how value is distributed within and across sectors, making visible patterns of concentration. For this, we combined DIEA-MGAP records on farm-size by sector with data on sectoral gross production values. In the case of forestry, due to the lack of official segmentation, we relied on public reports from leading companies, complemented by official 2010 data for smaller forest patches (MGAP, 2010).

These sources provide information separately for each sector (e.g., grains, dairy, forestry), which we refer to as (sub)-farms and (sub)-farmers. A (sub)-farm is defined as the portion of a farm engaged in a specific sector, and a (sub)-farmer as the corresponding operator. Because many farms participate in multiple sectors, the total number of (sub)-farms is about 30% higher than the number of farms (73,589 versus 57,074 units according to preliminary Agricultural Census 2024). This

difference reflects the degree of diversification in Uruguay, where more than one sector is often present in a single farm. Nevertheless, these segmentations offer valuable insights into the magnitude of monetary flows from different sectors, the distribution across farm-size classes, and therefore their concentration patterns across the agricultural landscape.

When information about production by class was unavailable in primary data sources, we allocated value proportionally to land area (e.g., horticulture, fruit, forestry). When available, value was distributed according to production output (e.g., dairy, grains, rice). For meat, we used the number of animals per class as a proxy for output, providing a more accurate estimate than land area alone. The resulting values were expressed in annual USD per (sub)-farm and grouped into five economic size classes (<0.1 M; 0.1–0.5 M; 0.5–2.5 M; 2.5–12.5 M; >12.5 M USD yr⁻¹).

2.5. Trends in area and productivity by sector

In addition to the cross-sectional comparisons, we also examined how these sectors evolved in their productivity and area occupied between 2005 and 2022. Our aim was not to reassess each indicator over time, but rather to place the current state within a dynamic context of expansion, intensification, and reconfiguration of land-based production. Time-series data were drawn primarily from DIEA-MGAP and complemented with other official sources. Missing values were estimated by fitting quadratic polynomial regression models using the `lm()` function in R, preserving observed data points while modeling gaps at the ends or within the series.

For the forestry sector, the long lag between plantation and harvest distorts standard productivity measures. We therefore reconstructed annual harvestable areas for *Pinus* and *Eucalyptus* by combining historical planting records and nursery supply data (1985–2023), thereby capturing rotation lengths and species-specific management regimes. Detailed modeling procedures are provided in Supplementary Material 1I.

3. Results

The allocation of Uruguay's land-based outputs toward foreign markets was reinforced during our study period. The largest sectors in terms of area, including meat, forestry, grains, and dairy, which occupied almost all of the farmland and 93% of Uruguay's continental area, currently allocate between 73% and 84% of their production to international markets (Table 1). Rice and vegetables each occupied less than 1% of the farmland but displayed very high and opposite market orientations for the same period: 97% of rice production was exported, whereas vegetables were almost entirely devoted to domestic consumption, with less than 1% exported. The fruit sector, also small in area, primarily served domestic markets, although 28% of production, especially composed of citrus, was exported. Between 2005–2007 and 2020–2022, Uruguay increased the share of farmland oriented toward exports from 74 to 83%, shifting the output of more than 1.5 million

hectares from domestic to foreign markets. Over the same period, apparent domestic consumption supplied by local production declined by 34, 12, and 12%, in meat, dairy and grains respectively, while it remained largely stable for rice and forestry, changing by less than 2%. Sectoral size relative to domestic demand was variable across sectors: rice showed the highest ratio (26× domestic demand), followed by forestry (5.4×), meat (4.1×), dairy (3.5×), and grains (2.6×). Fruits (1.1×) and vegetables (0.9×) were close to domestic equilibrium.

The multidimensional analysis revealed distinct impact profiles (i.e., the sustainability footprints) across sectors, using indicators expressed on a common comparative basis (Fig. 1, Supplementary Material 2A). Dairy occupied mostly mid-range positions across all indicators, showing no extreme highs or lows. Other sectors such as meat or rice showed the highest relative values in some groups of related indicators (e.g., biophysical indicators such as water use, eutrophication potential, net primary productivity, etc.) but lower for others (Supplementary Material 2E). For instance, meat was at the top of the ranking for its low environmental footprints (human appropriation of net primary productivity, greenhouse gas emissions, water use, eutrophication potential, and toxicity), but at the bottom for its per-area socioeconomic outcome indicators such as net foreign currency exchange, labor, and gross production value. Some sectors exhibited contradictory scores within the same dimension. For example, forestry showed lower relative pressures in indicators related to toxicity and eutrophication potential, and higher values of net primary productivity, but also higher relative water use. Vegetables showed high scores in labor and in the share of family farming, but had low scores for salary and labor formality. Across sectors, the gross production value varied by two orders of magnitude, from 194 to 19,239 USD ha⁻¹ yr⁻¹. When excluding fruits and vegetables and focusing on the five main agroexporting sectors, this variation in value ranged 11-fold (194 to 2034 USD ha⁻¹ yr⁻¹), with labor differing up to 5-fold within these sectors (Supplementary Material 2A).

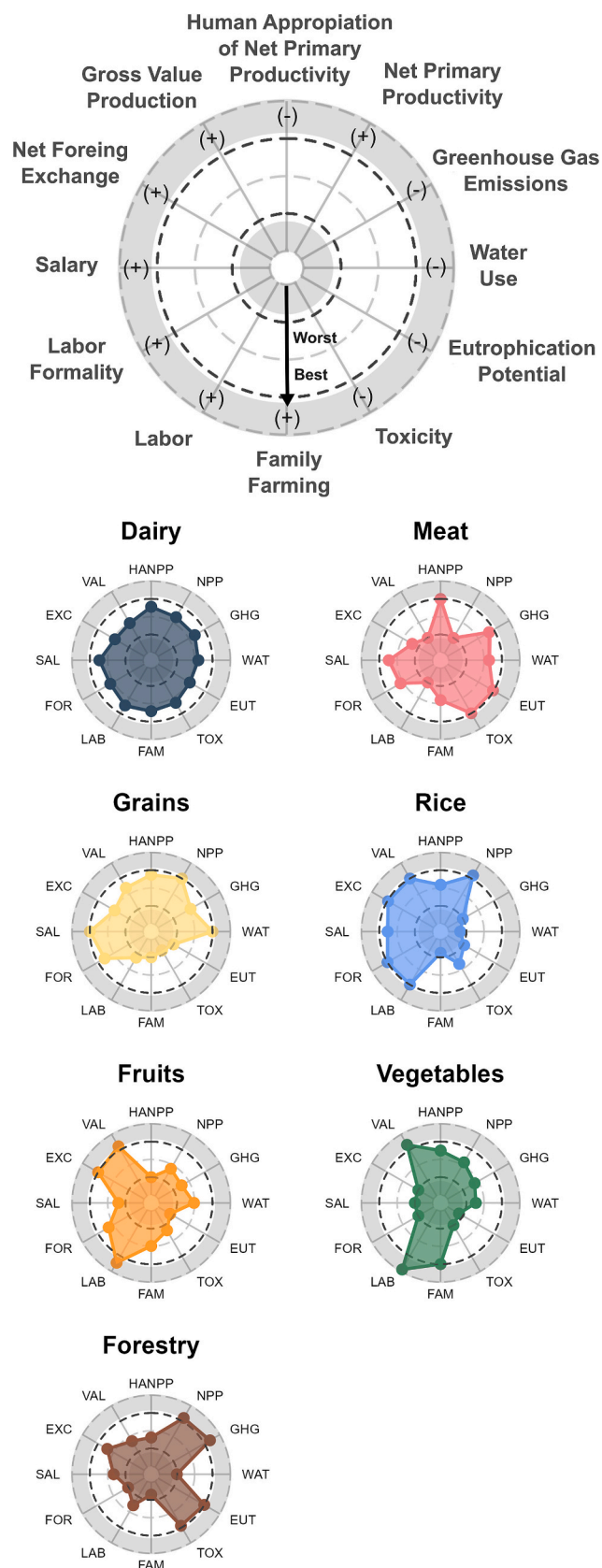
Ratios relating environmental pressures to socioeconomic outcomes varied across Uruguay's main agroexporting sectors (meat, dairy, grains, rice, and forestry; Supplementary Material 2B). Pesticide use per unit of gross production value ranged from 0.43 g of active ingredient per USD in forestry to 5.10 g per USD in grains, with dairy and rice displaying similar values (1.34 and 1.32 g per USD, respectively). Nutrient inputs per unit of value ranged from 2.37 g NPK per USD in forestry to 98.17 g per USD in grains, and comparable orderings were observed when ratios were expressed per unit of foreign exchange or labor. Water-related ratios followed a different pattern, with net water use per unit of value ranging from -1.39 m³ per USD in grains to 7.35 m³ per USD in rice, and forestry also exhibiting relatively high values (4.59 m³ per USD). Value generated per unit of labor ranged from 45.1 to 48.9 thousand USD per employed person in meat and dairy, to 202.3 thousand USD in grains, with rice and forestry occupying intermediate positions (72.4 and 76.0 thousand USD, respectively).

Variation across sectors was particularly high for greenhouse gas emissions, water use, and labor intensity, while socioeconomic indicators such as salaries, labor formality, and the share of family farming showed comparatively minor differences (Supplementary Material 2A).

Table 1

Share of production oriented toward export and domestic markets, and productive area, by sector.

Sector	Production destined to exports (%) (2005–2007)	Production destined to exports (%) (2020–2022)	Apparent domestic consumption supplied by national production (%) (2005–2007)	Apparent domestic consumption supplied by national production (%) (2020–2022)	Productive area (thousand ha) (2020–2022)	Productive area (% of farmland) (2020–2022)	Production / Apparent Domestic Consumption (2020–2022)
Meat	76	83	99	65	13,422	81	4.1
Dairy	47	75	99	87	665	4	3.5
Grains	65	73	81	69	1156	7	2.6
Rice	86	97	~100	99	144	<1	26.0
Fruits	29	28	88	80	30	<1	1.1
Vegetables	~0	~0	98	98	12	<1	0.9
Forestry	56	84	87	85	1105	7	5.4



(caption on next column)

Fig. 1. Sectoral footprint showing the array of biophysical and socioeconomic impacts expressed as sectoral intensities. Higher performance for a given indicator (e.g. lower pesticide use or greater labor intensity) is represented toward the outer portion of each plot. Indicators include: HANPP (Human Appropriation of Net Primary Productivity, %), NPP (Net Primary Productivity, kg dry matter ha⁻¹ yr⁻¹), GHG (Greenhouse gas emissions, kg CO₂-eq ha⁻¹ yr⁻¹), WAT (Net water use, m³ ha⁻¹ yr⁻¹), EUT (Eutrophication potential, kg NPK ha⁻¹ yr⁻¹), TOX (Toxicity, g active ingredient ha⁻¹ yr⁻¹), FAM (Family farming, % of producers), LAB (Labor, full-time equivalents per 100 ha), FOR (Labor formality, % of employment), SAL (Salary, USD hour⁻¹), EXC (Net foreign currency exchange, USD ha⁻¹ yr⁻¹), and VAL (Gross production value at the farm-gate level, USD ha⁻¹ yr⁻¹). To facilitate joint visualization of indicators spanning very different ranges, the inner and outer grey bands apply a non-linear visual scaling intended for qualitative comparison; original values and full quantitative information are provided in Supplementary Material 2A.

For some indicators, most sectors clustered within a relatively narrow range, with one or two sectors separating from the rest. For instance, water use per hectare and year ranged mainly between 79 and 3878 m³, but rice showed a much higher consumption of 14,950 m³ and grains uniquely displayed a net water surplus of 2047 m³. Similarly, labor was below 3 full-time equivalents per 100 ha in most sectors, except for vegetables and fruits, which reached 120 and 45, respectively. Toxicity showed a comparable pattern, ranging from 181 to 3927 g active ingredient ha⁻¹ yr⁻¹ for most sectors, with grains exhibiting a higher value of 7540 g active ingredient ha⁻¹ yr⁻¹.

Strong positive correlations were found among socioeconomic indicators (e.g., labor with gross production value, salary with labor formality) and among environmental ones (e.g., eutrophication potential with toxicity and greenhouse gas emissions). In contrast, production value was negatively associated with several environmental indicators, and labor intensity tended to correlate inversely with salary (Supplementary Material 2C). Some variations in one indicator were associated with simultaneous shifts in others (Supplementary Material 2A,D). For example, per unit of value produced, toxicity varied up to 16-fold, water use up to 19-fold, and eutrophication potential up to 14-fold across all sectors. Similarly, each unit of labor employed was associated with differences of up to 27-fold in eutrophication potential and over 30-fold in toxicity, even when excluding fruits and vegetables, the most labor-intensive sectors.

Despite scale-independent sectoral differences, aggregated impacts revealed clear differences in the contribution of sectors to national aggregates (Fig. 2). For example, while macronutrient inputs (i.e., eutrophication potential) were highest in fruits and vegetables (256 and 340 kg ha⁻¹ yr⁻¹, respectively, versus 2–145 for other sectors), they accounted for only 3.7% at the national scale. In contrast, some sectors made contributions at the aggregate level that were large relative to their per-hectare footprint and share of total farmland. For instance, the meat sector ranked second-to-last in net foreign currency exchange per hectare (169 USD ha⁻¹ yr⁻¹), yet it accounted for the largest national share (34%) (Fig. 2). Forestry (31%) and grains (18%) followed, even though they occupied only 6.6% and 7% of farmland, compared with 81.2% for meat. For other indicators, national totals were primarily accounted for by single sectors: meat supplied nearly half of total labor (46%), grains dominated nutrient mobilization (64.8%) and pesticide use (66.8%), and forestry accounted for most water consumed above the grassland reference used in the analysis (79%).

The distribution of gross production value varied across farm-size classes and sectors, reflecting differences in land area and the number of farms involved (Fig. 3). Small farms (<0.1 M USD yr⁻¹) accounted for 81% of productive units or (sub)-farms and 23.8% of land, but captured only 15.8% of gross production value, largely contributed by the meat sector (64.2% of this size class). In contrast, very large farms (>2.5 M USD yr⁻¹) represented less than 0.5% of all (sub)-farms, occupied 9.7% of farmland, and captured 28.1% of gross production value, primarily from forestry and grain sectors (30.1% and 57.1% of the two largest size-

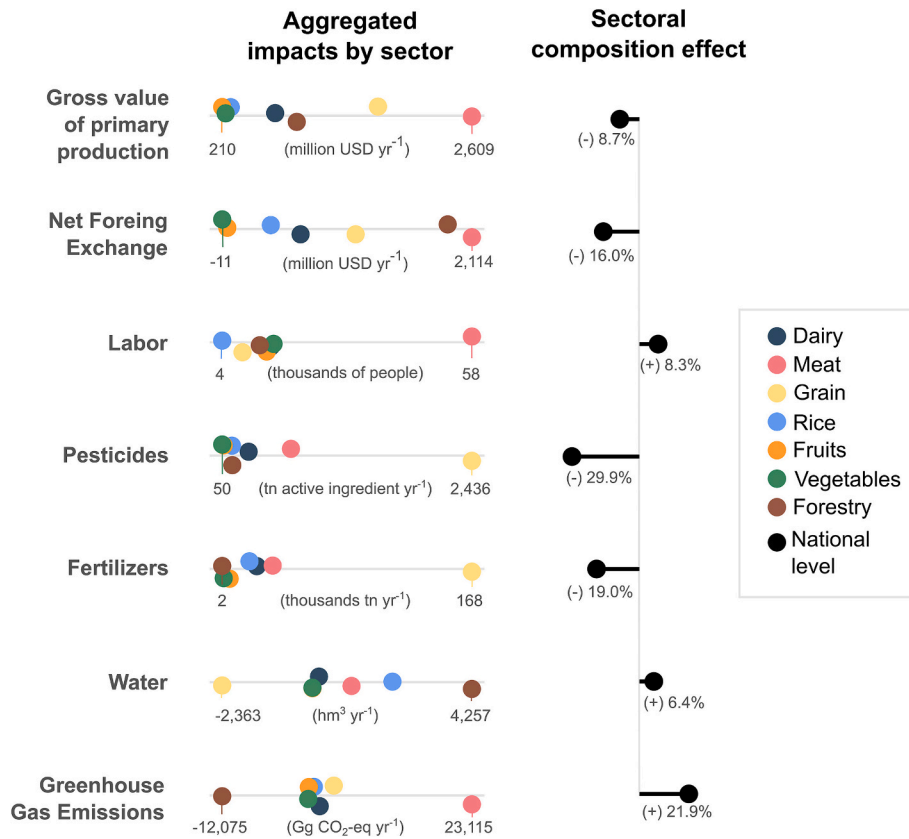


Fig. 2. Aggregated sectoral impacts and the effect of sectoral composition on national outcomes. The left panel shows the aggregated (absolute) impacts of individual productive sectors across selected socioeconomic and biophysical indicators in Uruguay. Values are reported in absolute terms to highlight that sectors with high per-hectare intensities may contribute little in aggregate, whereas extensive sectors can dominate national outcomes despite lower unit-area intensities. The right panel shows the effect of sectoral composition on national outcomes, estimated through a backcasting scenario that holds the sectoral composition fixed at its initial configuration (2005–2007) while applying current sectoral footprints. Details of the backcasting procedure are provided in Supplementary Material 2 K.

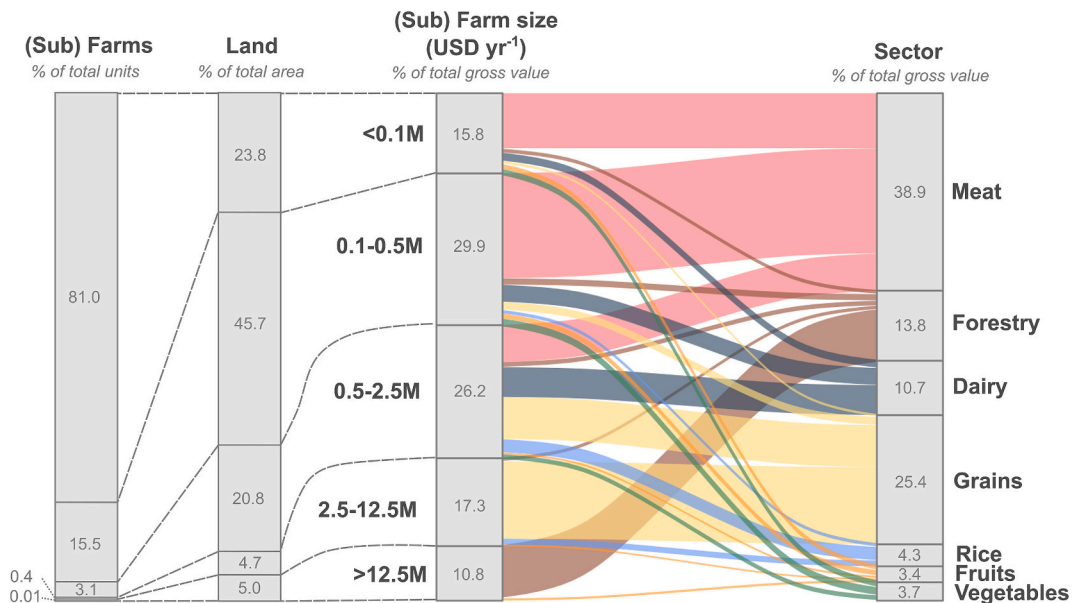


Fig. 3. Distribution of gross production value across (sub) farm-size classes in Uruguay. The figure shows (i) the share of total (sub)-farms in each class, (ii) the proportion of the farmland they occupy, (iii) the flow of gross production value through each class, and (iv) how the value generated by each sector is distributed across farm-size categories. Sectors are ordered by value generated per unit land area (from lowest to highest). Here, (sub)-farms and (sub)-farmers refer to the portions of farms and their operators associated with a specific sector, and because many farms participate in multiple sectors, the total number of (sub)-farms exceeds the actual number of farms (see Methods for details).

classes combined). Intermediate-scale operations (0.1–2.5 M USD yr⁻¹) were associated with 66.5% of the land and 56.1% of gross production value, dominated by meat (42.7%), dairy (15.4%), grains (14.7%), and forestry (14.7%), with the remaining 12.5% from rice, fruits, and vegetables.

Between 2005 and 2022, sectors displayed distinct trajectories in production, driven by different combinations of area and productivity change (Fig. 4). Grains experienced a rapid expansion in cultivated area, peaking at 1.5 Mha in 2015 with limited productivity gains. This was followed by a contraction in area and marked productivity improvements, resulting in a net increase of 164% in total production relative to the baseline. Forestry expanded more steadily, with a sustained increase in planted area alongside productivity gains, resulting in a 106% increase in total production. In contrast, vegetables, dairy, rice, and meat all contracted in area, though with varied production outcomes. Dairy achieved the largest productivity increase (90%), offsetting a 27% area loss and resulting in a 44% rise in production. While sector-specific improvements played a major role, this growth has also been linked to the greater availability of feed concentrates, partly derived from Uruguay's expanding grain production and partly from imports. Rice followed a similar pattern, with a 17% area reduction but a modest 20% gain in output. Vegetables increased productivity by 55%, nearly recovering baseline production levels despite losing 41% of cultivated area. Meat registered the smallest relative productivity gains (32%) and a modest 5% area loss, but given its large initial scale, recorded the largest absolute land reduction (731,800 ha). Fruit production remained stable in area but underwent strong internal shifts, with declines in oranges and apples offset by growth in olives, grapes, and lemons.

To quantify the footprint of the sectoral composition shifts that took place in the study period, we constructed a “past sectoral composition” scenario. To do so, sectoral shares observed two decades ago (2005–2007) were applied to present-day agricultural land availability, generating a counterfactual allocation of hectares by sector (Supplementary Material 2K). For each sector, current area-specific intensities were then used to estimate a subset of aggregate outcomes (Fig. 2),

including biophysical (*i.e.*, water, fertilizer and pesticide use, greenhouse gas emissions) and socioeconomic (*i.e.*, labor, gross value of production and net foreign exchange) dimensions. Under this setup, production levels varied proportionally with changes in sectoral areas, and economic indicators were derived from the resulting output under simplified assumptions, including constant baseline imports and input use scaling with production. In this scenario, aggregate national outcomes differed markedly from current values, showing contrasting directions. Without the observed compositional changes, gross production value and net foreign currency generation would have been 8.7% and 16.0% lower, respectively, while pesticide use and nutrient inputs would have been reduced by 29.9% and 26.5%. In contrast, greenhouse gas emissions and total water use would have been higher by 21.9% and 6.4%, respectively, and total labor demand would have been 8.3% higher.

4. Discussion

Our results provide differentiated support for the hypotheses guiding this study. The observed patterns are broadly consistent with expectations regarding the deepening of the structural role of agroexporting countries and their association with the pursuit of higher economic output (H1), as well as with the mechanisms connecting sectoral change to concentration processes (H3). In contrast, the evidence for the hypothesis associating higher economic output with systematically deeper environmental and social footprints (H2) appears more conditional. This asymmetry in hypothesis support frames the discussion that follows.

4.1. The pull of global insertion shaping national land use

Uruguay's agricultural landscape has become increasingly oriented toward external markets, with the share of farmland devoted to export-oriented production rising from roughly three quarters at the beginning of the 21st century to more than 80% today. This exceptionally high level of export orientation (Howden and Zammit, 2019; Kastner et al.,

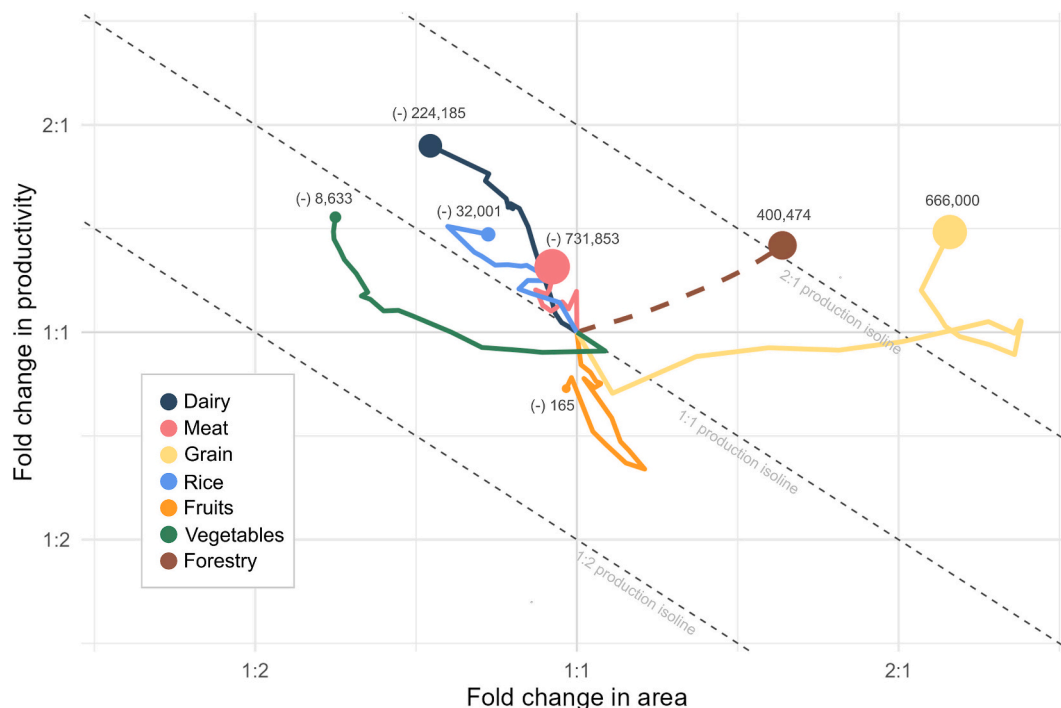


Fig. 4. Trajectories of Uruguay's main agricultural sectors (2005–2022) in terms of extensification and intensification. Values represent fold changes in area and productivity relative to 2005 (baseline = 1), smoothed with a 5-year centered moving average. For forestry, only the net change between the initial period (2005–2007) and the final period (2020–2022) is shown as a dashed line, to avoid distortions from irregular harvests during the sector's early development (Supplementary Material 1I). Dot size and annotations on the panel indicate the absolute change in area (ha), whether gained or lost.

2021) can be understood as the result of rising production in nearly all major sectors, combined with a deepening integration into global trade. By contrast, although population increased by 6% from 2003 to 2023 (INE, 2023), changes in total domestic demand by sector varied from positive (meat, grains, forestry) to negative (dairy, rice, fruits and vegetables), showing diverse trends in *per capita* consumption patterns. Together, these dynamics effectively shifted about 1.5 million hectares that once supplied domestic markets into global commodity chains, consolidating the country's agroexport profile.

Within this predominantly export-oriented territory, sectors differ sharply in how far their size exceeds domestic needs. Using the ratio of total production to apparent domestic consumption, we observed that meat and forestry produced volumes that were roughly 4.1 and 5.4 times larger than domestic demand, while for dairy and grains the excess was about 3.5 and 2.6 times, respectively. By contrast, fruits and vegetables remained close to balance with local consumption, and rice was an extreme export-oriented case that would virtually disappear if driven only by local demand. These disparities show that the size distortion associated with the agroexport model is highly asymmetric across sectors, rather than a uniform scaling-up of the entire agricultural economy (Liu et al., 2013; Ayompe et al., 2021; Meyfroidt et al., 2024). Importantly, the size distortion described here is not equivalent to land occupation: for instance, while the meat sector covers more than 80% of the country's farmland, its oversizing relative to domestic demand was lower than that of much smaller sectors such as forestry or rice. This contrast highlights that the imprint of external markets cannot be inferred from spatial dominance alone.

Our results also showed that the way sectors achieve these distorted sizes was different. Forestry and grains expanded production mainly through increases in area, while the rest of the sectors contracted, partially compensating the loss of area with sustained productivity growth (vegetables, fruits), or even offsetting it considerably (dairy, rice). At the aggregate level, this reconfiguration of sectors resulted in higher national economic output and foreign exchange generation. This occurred despite the contraction of some high-value (per hectare) sectors, highlighting the dominant role of sectoral composition in shaping aggregate economic outcomes. These findings illustrate how rising production, sustained external demand, and relatively low institutional frictions interact to amplify sectoral disparities, reinforcing the dominance of export-oriented production across the landscape (Liu et al., 2013; Kastner et al., 2021). This provides empirical support for the mechanisms proposed in our first hypothesis, by showing how productivity gains and shifts in sectoral composition under broadly stable domestic demand jointly translate into higher aggregate economic outcomes.

4.2. Sectoral composition and scale effects on sustainability outcomes

Our analysis indicates that sustainability outcomes in agroexporting countries are shaped not only by the intrinsic footprints of individual sectors, but also by their relative scale within the export-oriented productive space. In line with our second hypothesis, higher economic output was frequently accompanied by greater resource mobilization and labor inputs, leading to increased biophysical pressures. However, our results also showed that these pressures were sector-specific, meaning that aggregate sustainability outcomes depend critically on which sectors expand beyond domestic demand, a mechanism that becomes increasingly influential as a larger share of farmland is oriented toward external markets.

Sector-to-sector comparisons confirmed that increasing economic output was consistently associated with higher biophysical pressure, although the specific form and magnitude of such pressure depends strongly on the sector considered (Jobbágy and Sala, 2014; Meyfroidt et al., 2022). These sectoral differences were particularly evident when biophysical outcomes were evaluated in relation to socioeconomic ones, as major production activities displayed contrasting environmental

footprints per unit of value, labor, or foreign exchange generated. Such variability reflects the markedly different combinations of production intensities and sector-specific trade-offs that characterize major land-based activities in Uruguay (Paruelo et al., 2024).

For instance, the meat sector, the historical backbone of Uruguay's agricultural system, is characterized by an extensive production profile: it maintains large areas of natural and semi-natural ecosystems with relatively low biophysical pressures per unit of land (Paruelo et al., 2024; Aldabe et al., 2024), but also generates limited socioeconomic returns on the same basis. Consistent with this profile, we found that this sector had by far the lowest gross production value per hectare, reaching approximately one-quarter of that observed in the next lowest sector, forestry. Nevertheless, the meat sector also included a substantial share of family farms, reinforcing its role in maintaining territorial embeddedness and sustaining rural communities.

Grain production displayed a contrasting profile, generating significant gross production value and foreign exchange per unit of area but at the cost of a heavy reliance on imported inputs (22.5% of their gross production value, compared to 1–9% in other sectors such as forestry or dairy), high pesticide use, and the circulation of large nutrient volumes with risks of losses and contamination (Jobbágy et al., 2021; Díaz et al., 2021). From a social perspective, however, the sector was associated with the highest average wages and comparatively low levels of labor informality.

Forestry, in turn, reflected a highly transformative land-use profile: it was among the least toxic activities and mobilized relatively few nutrients, yet placed strong pressures on ecosystem functioning, a pattern consistent with previous studies (Paruelo, 2012; Alonso et al., 2024). Within our dataset, forestry exhibited a net primary productivity increase exceeding 3.5-fold relative to the meat sector, alongside significant costs in terms of water use. In addition, our results indicated comparatively high levels of labor informality associated with forestry-related activities. This characterization is in line with previous analyses that have documented structural vulnerabilities and persistent circuits of labor informality within the forestry sector, particularly in fuelwood and low-value wood chains (Carámbula and Piñeiro, 2006; Ackermann and Cortelezzi, 2018). Such contrasts are not merely descriptive differences between sectors but reflect fundamentally different pathways through which economic output is coupled with biophysical and social pressures.

Under conditions of marked sectoral heterogeneity, aggregate sustainability outcomes become inherently sensitive to how farmland is distributed among sectors. This dynamic is clearly reflected in Uruguay, where the strong orientation toward external markets has been accompanied by substantial shifts in sectoral composition over the last two decades. In this context, our results highlight the dominant role of sectoral composition in shaping aggregated sustainability outcomes. This non-uniformity in performance across dimensions was evident when outcomes were examined through the past composition scenario. Higher economic output and foreign exchange generation co-occurred with increases in some pressures (e.g., pesticide use and nutrient inputs) and reductions in others (e.g., greenhouse gas emissions, total water use, and labor demand), revealing that sector-led intensification can reshape national sustainability outcomes through non-aligned changes across dimensions (Foley et al., 2011; Meyfroidt et al., 2022; Kastner et al., 2021). While uncertainty was not explicitly quantified at the sectoral level in our study, and therefore not in the derived scenario, the exercise still provides a robust signal of how shifts in sectoral composition are likely to affect dimensions differently. Together, these patterns indicate that agroexport-driven intensification amplifies environmental pressures (Wu et al., 2024), but does so in sector-specific ways, opening a wide spectrum of (un)sustainable trajectories.

Although our analysis does not prescribe specific sectoral paths, it indicates that sectors are not bound to maintain their current footprints. Each one can potentially act on the dimensions where pressures are most critical. In this context, studies suggest that the meat sector in Uruguay

can improve its productivity and income per hectare preserving or enhancing its natural basis (Ruggia et al., 2021; Aldabe et al., 2024). The grain sector, in turn, shows scope for reducing its pesticide dependence and contamination risks (Garibaldi et al., 2023), and forestry could move toward models with milder ecosystem transformations (Jobbágy et al., 2006). Moreover, complementarities across sectors could help balance positive and negative outputs, not only at the national level but also at finer scales; for instance, within watersheds, where water and habitat trade-offs are decisive, or near urban centers, where employment gains carry particular weight.

4.3. Concentration and governance challenges

How an agroexporting country navigates its structural position is critical for steering its sustainability outcomes (Gudynas, 2013; Lashkari et al., 2022). Importantly, becoming and remaining agroexport-oriented is not an unavoidable outcome of geography or biophysical endowment, but the result of a complex interplay of these with historical, political, and market forces (Bridge, 2008; Baraibar-Norberg, 2020). In Uruguay, policy frameworks such as the Law 15.939 (Forestry Law, 1987) or Law 16.906 (1998), with their tax incentives and subsidies, played a decisive role in consolidating the current land-use model (Durán and Salgado, 2013). These examples show that national choices, alongside global market dynamics, actively reinforced the country's export orientation and current sectoral composition (Baraibar-Norberg, 2020).

Diversification and increasing economic complexity have been widely stated goals for agroexporting countries. Yet structural change is not determined solely by domestic decisions, but also by the global product space, which constrains which new sectors can emerge competitively (Hidalgo, 2023; Aragie et al., 2023). This structural inertia helps explain the persistence of agroexport specialization over extended periods. Within these constraints, diversification often occurs through the introduction of new agricultural products (Hidalgo, 2023). Although such changes may not fundamentally alter the country's structural role in the global economy, our results suggest that they can significantly reshape sustainability outcomes at the country level. Understanding and anticipating these potential sectoral reconfigurations is therefore critical for promoting sustainable futures.

Recognizing the structural, functional, and political differences between sectors does not mean accepting fragmentation or naturalizing their negative impacts (Bridge, 2008; Gudynas, 2013). On the contrary, it creates the conditions to collectively discuss how priorities are set, how responsibilities are distributed, and what kind of development a country seeks to sustain. Decisions about land-use change are therefore never just technical; they are embedded in competing visions and priorities (Martin et al., 2024). In agroexporting countries like Uruguay, where land-based production is structurally central, the territory becomes the arena where multiple sustainability narratives coexist, each selectively highlighting certain benefits while downplaying or omitting costs (Sumberg et al., 2023). These narratives, shaped by worldviews and material interests, are all partial, and understanding them as such is essential for effective governance.

In line with our third hypothesis, our results point to increasing economic concentration across a small number of sectors and actors, a pattern that is widely associated with growing power asymmetries (Clapp et al., 2025). Moreover, the ongoing trends in Uruguay are consistent with a broader process of land consolidation and capital-led intensification commonly observed in export-oriented agrarian systems (Baraibar-Norberg, 2020; Graziano-Ceddia, 2019). At the core of these asymmetries lies the structure of land ownership: with property highly concentrated and land prices steadily rising, entry barriers for new actors become prohibitive, narrowing the scope of inclusive debates. Large landholders retain the autonomy to pursue whichever uses are most profitable, which may be weakly aligned with broader sustainability goals at the national level. Policymakers, however, retain some capacity to influence these dynamics through a range of

distributive and regulatory instruments: from progressive land taxation, prohibitions and subsidies to more innovative tools such as participatory land-use planning, transparency instruments, and institutional reforms that can reshape incentives and rebalance negotiations (Baraibar-Norberg, 2020; Clapp et al., 2025).

From an analytical perspective, our findings highlight the importance of robust and transparent information systems for understanding and governing land-based production systems in agroexporting countries. In this context, the development of permanent, cross-sectoral observatories has been identified in the literature as a mechanism to support accountability and evidence-based governance (Bridge, 2008; Wood et al., 2022; Díaz et al., 2021). While Uruguay benefits from integrated public statistics (the very same that made our analysis possible), existing information remains fragmented and poorly visible, illustrating the broader challenges faced by agroexporting countries in institutionalizing sustained, cross-sectoral monitoring.

4.4. Limitations of this study

From a methodological standpoint, this study has several limitations that should be acknowledged. Our multidimensional comparison relies on simplifying assumptions. Estimates for variables such as pesticide use, water consumption, and nutrient inputs assume some degree of homogeneity within sectors, which may not fully capture on-the-ground variability. Nevertheless, given the magnitude of differences observed across sectors, these assumptions are unlikely to overturn the main patterns. Still, exploring within-sector variability and its impacts remains crucial for identifying potential improvements and enhancing positive contributions. Our analysis also involves simplifications in the assessment of economic concentration. We focused on flows through what we term (sub)-farms (see [Materials and Methods](#)) rather than actual ownership structures, and did not capture higher-order complexities such as firms managing multiple holdings across different activities. This implies that the actual degree of concentration is likely higher than reported and deserves further investigation.

Finally, this study also has a constrained scope, as we did not examine other dimensions highly relevant to sustainability debates, such as soil carbon, biodiversity, education or gender equity. Including these would likely reinforce our finding that no sector performs uniformly well across all metrics. We also did not explicitly analyze the territorial embedding of value chains; for example, rice production in Uruguay is geographically concentrated and closely intertwined with local cultural and socio-economic contexts. Forestry, on the other hand, expanded as a highly disruptive sector that challenges the dominant treeless nature of the landscape. Nonetheless, our focus on the national scale allows us to capture broader structural processes while necessarily abstracting from these local specificities. These limitations are consistent with the study's objective of capturing national-scale structural dynamics rather than fine-grained local processes.

4.5. Conclusions

In Uruguay, as in most agroexporting countries, sustainability and development debates are intertwined with agricultural production, which in turn is linked to both local and overseas demands. Export-oriented production occupies most of the Uruguayan territory and still expands, showing a highly dynamic sectoral composition and output. While multiple potential sectoral arrangements can fill the agroexporting niche, in practice, configurations that operate at large scales and concentrate economic value in the hands of relatively few actors seem to expand more rapidly, following the pace of the expansion of the global commodity trade.

Our analysis shows that what ultimately shapes national sustainability outcomes is not the intrinsic performance of sectors alone, but how their distinctive footprints scale with changes in their relative size as they open to external demand and investment. Higher aggregate per-

hectare economic output in our dataset tended to be associated with higher biophysical and human inputs, confirming the existence of real trade-offs. However, these trade-offs were neither uniform nor unavoidable. Different sectors translate economic expansion into pressures along distinct dimensions, such that changes in sectoral composition redistribute impacts rather than simply intensifying them across the board. This creates a non-trivial margin for collective choice and policy deliberation, whereby alternative sectoral configurations can sustain similar levels of economic output while emphasizing different combinations of environmental and social trade-offs.

The evidence also highlights that sectoral trajectories are not uniform. Sectors with higher capital concentration are structurally better positioned to leverage global demand, reinforcing their growth through economies of scale. This concentration translates into asymmetries of power, shaping narratives about which trajectories are desirable, which benefits should be emphasized, and which costs can be downplayed. Consequently, sustainability debates in agroexporting countries take place in contested political arenas, where global demand, domestic policy, and structural concentration interact to either entrench dependence or open pathways toward more sustainable alternatives.

Together, our results suggest that sustainability outcomes in agroexporting countries such as Uruguay depend less on optimizing individual sectors in isolation and more on how sectoral configurations evolve over time, particularly with respect to relative scale, concentration, and the distribution of impacts and benefits. While this study does not evaluate specific policy instruments or governance arrangements, the diversity of viable sectoral configurations identified here highlights the existence of meaningful scope for collective choice. Understanding how public policies, institutional settings, and power relations interact with these configurations therefore remains a critical avenue for future research.

CRedit authorship contribution statement

Tomás Milani: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Federico Bizzozero:** Writing – review & editing. **Néstor Mazzeo Beyhaut:** Writing – review & editing. **Matilda Baraibar-Norberg:** Writing – review & editing. **Juan Manuel Piñeiro-Guerra:** Writing – review & editing, Formal analysis. **Lucía Rodríguez Tricot:** Writing – review & editing. **Lucas A. Garibaldi:** Writing – review & editing, Project administration, Funding acquisition. **Esteban G. Jobbágy:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT 5.0 in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2026.181828>.

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