Assessing the performance of agricultural systems in the inland and coastal regions of Northern Portugal using indicators: establishing the foundation towards better agricultural practices

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Abstract

This study conducts a comprehensive evaluation of agricultural systems in the distinct coastal and inland regions of Northern Portugal. Employing key indicators, including soil erosion, nitrogen surplus, irrigation practices, Agricultural Gross Domestic Product (GDP), and crop yield, the analysis reveals statistically significant disparities and unique challenges in each region. The coastal areas, marked by higher agricultural GDP, exhibit distinct economic dependencies on agriculture, while the inland regions face challenges related to water scarcity, soil erosion, and rural isolation. The looming threat of climate change adds complexity to these dynamics, further highlighting the need for region-specific, sustainable agricultural practices. In the coastal regions, integrated crop-livestock farming, organic farming, and intercropping emerge as strategic choices, aligning with economic robustness. Inland regions require nuanced approaches, addressing water scarcity through improved irrigation efficiency, implementing climate-resilient terrace farming, and fostering resilient farming communities. The study emphasizes a bottom-up approach, considering the advantages, disadvantages, and climatic variations of each region, to establish a foundation for sustainable agriculture in Northern Portugal. While offering valuable insights, the study acknowledges limitations and advocates for ongoing collaboration to refine strategies in response to evolving agricultural landscapes.

Acknowledgments

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1. Introduction

In an era marked by climate change, environmental degradation, and increasing global food demand, the imperative for sustainable agriculture has never been more crucial. Sustainable agriculture transcends a merre buzzword, embodying a comprehensive approach that seeks to harmonize ecological integrity, economic viability, and social equity in food production. At its core, this paradigm recognizes the interconnectedness of environmental health, agricultural productivity, and the well-being of communities. Sustainable agriculture addresses a spectrum of challenges. From mitigating soil erosion and degradation to optimizing water use efficiency and curbing the adverse impacts of synthetic fertilizers and pesticides, sustainability is a cornerstone in safeguarding the planet's resources. Beyond conservation, sustainable agriculture contributes to resilient ecosystems, enhances food security, and fosters equitable livelihoods for farming communities.

Climate change and sustainable agriculture are inextricably linked, as evidenced by the profound impact of climate-induced land degradation on agricultural productivity. The consequences are dire, with a quarter of the global land area now classified as degraded, influencing the lives of 1.5 billion people (Bai et al.,2008). As per the Global Assessment of Land Degradation and Improvement (GLADA), anthropogenic activities coupled with climate change result in the loss of 15 billion tons of fertile soil annually. This degradation has far-reaching effects, contributing to mass migrations and the abandonment of 500 million hectares of farmland due to drought and desertification, as reported by the United Nations Environment Programme in 2017. Understanding the intricate relationship between climate change and sustainable agriculture is crucial, and as we turn our focus to the agricultural landscape of northern Portugal, it becomes evident that the challenges posed by climate change are not uniform across regions, demanding tailored solutions for sustainable practices in response to the unique characteristics of each locale.

The northern part of Portugal boasts a distinctive landscape, featuring a rectilinear coastline with a consistent NNW-SSE orientation, extending from Cape Silleiro near Baiona to Espinho, just south of Porto (Vieira, 2013). The region's topography includes the Rias of Galicia to the north of Cape Silleiro, creating a deeply indented coast that contrasts with the straighter southern stretch. Various geological explanations, including subsidence, tectonic depressions, and weathering during the Tertiary, have been proposed to elucidate the formation of these coastal features (Vieira, 2013). Furthermore, the Porto-Tomar fault is suggested to play a role in shaping the rectilinear coastline from Cape Silleiro to Espinho (Vieira, 2013). The climate in northern Portugal exhibits variations in sunshine hours, rainfall, precipitation amount, water temperatures, relative humidity, absolute humidity, and the Humidex throughout the year, with potential implications for agricultural practices in the region. The sunniest month, July, offers 10 hours of sunshine per day, while January experiences the most rain days with 13, and October has the highest precipitation amount (World Data Center for Climate, n.d.).

As we consider the unique characteristics of northern Portugal, it becomes imperative to explore the impact of climate change on its agricultural sector. Studies suggest that precipitation in the northern part of the country may decrease by approximately 15% (Schleusser, 2019). Climate change has introduced asymmetric warming trends, with the most significant increases observed in minimum temperatures during winter and spring (De Dios Miranda et al., 2011). Furthermore, alterations in the regional precipitation regime, particularly a substantial decrease in March, are attributed to changes in the North Atlantic storm tracks and the North Atlantic Oscillation (NAO) pattern (Trigo & DaCamara, 2000; Vicente-Serrano et al., 2011). This evolving climate scenario raises concerns about its implications for agriculture, as evidenced by studies linking climate parameters to grapevine productivity in the Douro region (Santos et al., 2010). The climatic disparities between the inland and coastal regions of Northern Portugal significantly influence agricultural practices, leading to distinct approaches in each area. The coastal region, with its milder temperatures and higher precipitation, is conducive to a diverse range of crops (Beck et al., 2018). Extensive pastures, forage maize, and vineyards thrive along the coast, benefiting from the favorable climate and sufficient water availability. On the other hand, the inland region, with its more variable temperatures and lower precipitation, necessitates adaptive agricultural practices (Beck, et al., 2018). Olive groves, vineyards, and nut cultivation are prevalent in the inland region, reflecting a focus on crops resilient to the continental climate. The unique case of the Douro Valley, situated inland, further highlights the region's specialization in viticulture, contributing to the renowned production of Port wine (Santos et al., 2010). These differing agricultural practices underscore the intricate interplay between climate and cultivation strategies, emphasizing the need for region-specific approaches in Northern Portugal. The agricultural sector in northern Portugal may face challenges in adapting to these changing climate conditions, emphasizing the urgent need for sustainable agricultural practices.

This study embarks on a comprehensive exploration of sustainable agricultural practices in the diverse landscape of northern Portugal. The primary objective is to establish a foundation for recommendations that align with the distinct characteristics of the region. The investigation will start by delving into the background of sustainable agriculture, elucidating the imperative need for new approaches in the face of climate change and the shortcomings of existing agricultural methods. Subsequently, an in-depth analysis of the prevailing agricultural methods in northern Portugal will be conducted, addressing their limitations, particularly the variations observed between the inland and the coastal areas. Indicators such as N surplus, soil erosion, water irrigation, crop yield, and agricultural gross domestic product will serve as pivotal metrics in the statistical analysis, offering a comprehensive understanding of the northern region's agriculture on the inland and coast. The paper will then provide an overview of the employed research methodology, underscoring its strengths and limitations The culmination of this study will involve a meticulous examination of the statistical findings, leading to the development of nuanced and region-specific suggestions for sustainable agricultural practices tailored to northern Portugal's diverse landscape.

2. Background information

2.1 The Need for Sustainable Agriculture

The need for sustainable agriculture in Northern Portugal is further underscored by the extensive environmental impact of conventional farming practices. Current agricultural trends contribute significantly to climate change, as evidenced by the extensive greenhouse gas emissions associated with livestock. Livestock production alone accounts for 70% of all agricultural land and 30% of the planet's land surface, leading to deforestation, habitat loss, and soil degradation, especially in regions like Latin America (FAO, 2006). The inefficiencies in protein production through animal feeding are striking, with estimates suggesting that 80% to 96% of the protein in cereal and leguminous grains fed to animals is not converted to edible protein (Smil, 2002). Meat consumption, driven by a Western diet, poses a substantial threat to the environment. The demand for meat is associated with extensive land use, as the world's population, especially in developed countries, consumes meat at a rate that would require two-thirds more agricultural land than is presently used (Smil, 2002). This demand contributes to deforestation, as seen in the Amazon, where 70% of previously forested land is now occupied by pastures (FAO, 2006). The inefficiencies in meat production are not only environmental but also economic, as livestock production utilizes vast amounts of resources such as water and grain, contributing to the overuse of water and land degradation.

Transitioning from the environmental impacts of conventional farming to the broader challenges faced globally, sustainable agriculture has become an imperative need. The urgency for widespread adoption is underscored by the challenges posed by climate change on agricultural productivity. The impacts of climate change on agricultural productivity are glaring, with projections indicating a significant reduction in crop yield, particularly in southern Europe, including Portugal (Hunter et al., 2021). The region faces heightened risks of heat waves, droughts, and floods, which have already led to diminished yields of key crops such as grapevine, durum wheat, and olive (Schleussner, 2019). These climatic shifts also expose animals to increased heat stress during summer, further compromising the agricultural sector (Hunter et al., 202).

The changing climate conditions in Portugal pose a direct threat to food production, elevating the pressure on water resources and risking food security (Rolim et al., 2017). Projections indicate an increasing demand for irrigation to sustain crop yields, particularly in the face of decreasing water availability in southern Portugal (Rolim et al., 2017). The consequences are profound, with scenarios showing a continuous decrease in maize and wheat yields, attributed to expected temperature increases and intensified drought and heat stresses (Yang et al., 2017, 2019). For instance, the projected decline in maize yields and the negative impact on mean wheat yield (−27% to −14%) present formidable challenges for sustaining agriculture in the region (Yang et al., 2017, 2019).

The implications of climate change extend beyond crop yield reduction to encompass broader issues such as desertification. Portugal, among other European countries, faces increasing desertification, leading to significant consequences on land use (Mirzabaev et al., 2019). Specifically, the IPCC's special report on climate change and land highlights the escalating impact of desertification in Portugal, emphasizing the urgency for sustainable land management practices (Mirzabaev et al., 2019). In the Alentejo region of Portugal, a recent study by Yang and colleagues identifies drought stress as a major limiting factor for potentially attainable wheat yields, resulting in substantial yield gaps (Yang et al., 2020). The severity of water stress in southern Portugal, particularly during April–June, is projected to increase, further exacerbating challenges in the agricultural sector (Rocha et al., 2020; Yang et al., 2019). The pressure on green freshwater resources, particularly in central littoral and western coastal areas, adds another dimension to the complex water-related challenges faced by the region (Quinteiro et al., 2019).

2.2 Agricultural and Pedoclimatic Variations in Northern Portugal

Table 1: Main Crops Grown in Each Region

Region	Crop area (ha)	Crop name
coastal	95197.8	Extensive pasture
coastal	36199.4	Forage maize
coastal	34089.1	Other forage
coastal	21035.7	Irrigated maize
coastal	20561.6	Vineyard
inland	145280.3	Extensive pasture
inland	80040.3	Olive groves
inland	62362.7	Vineyard
inland	27707.3	Nuts
inland	19707.6	Almonds

The agricultural practices in Northern Portugal exhibit a fascinating interplay between the coastal and inland regions, each characterized by distinct dynamics that contribute to the region's diverse agrarian landscape. Along the coastal expanses, where the temperate influence of the Atlantic Ocean prevails, a mosaic of agricultural activities unfolds. Covering extensive pastures (95,197.8 ha), the coastal areas serve as a foundational ground for thriving livestock farming. Complementing this, the cultivation of forage maize (36,199.4 ha) and other forage crops (34,089.1 ha) supports a robust livestock industry, showcasing the adaptability of the region.

As we explore the inland region, the agricultural practices transform, revealing a hinterland where tradition and specialization coalesce. Vast pasturelands (145,280.3 ha) suggest a reliance on grazing animals and grass-forage for animal feeding, and Olive groves (80,040.3 ha) flourish in the inland's distinct climate, adding diversity to the agricultural panorama. The persistence of vineyards (62,362.7 ha) underscores the enduring significance of viticulture, while the cultivation of specialized crops, including nuts such as almonds (27,707.3 ha), introduces additional layers of complexity. This intricate narrative of coastal and inland agricultural practices finds resonance in the diversity of crops grown. The coastal regions, with their level topography, facilitate the cultivation of irrigated maize (21,035.7 ha) and extensive vineyards (20,561.6 ha), representing a fusion of arable farming and viticulture. Meanwhile, the inland regions showcase a spectrum of crops, from vast pastures to olives, nuts, and vineyards (62,362.7 ha), capturing the nuanced interplay of tradition and innovation.

Within this inland expanse lies the singular Douro Valley, a UNESCO World Heritage site known for its cultural and environmental prominence. Covering 24,600 hectares, the Alto Douro Vinhateiro stands as a testament to the delicate equilibrium achieved between resource management and landscape preservation (Figueiredo,2020). The steep terraced slopes and a strong emphasis on viticulture, particularly wine production, make the Douro Valley an exemplar of seamless integration of agricultural practices with cultural and environmental conservation.

As we delve into the unique case of the Douro Valley, we witness not only a geographical distinctiveness but also a commitment to sustainable practices. The steep terraced slopes, while challenging, contribute to the preservation of the living landscape (Figueiredo,2020). This commitment is crucial, especially considering the Douro Valley's UNESCO recognition, signifying its cultural and environmental significance. The valley serves as an emblematic case where agricultural practices harmonize with the conservation of cultural heritage, exemplifying a delicate equilibrium that reverberates through the region's agrarian landscape (Figueiredo,2020).

In essence, the agricultural practices in Northern Portugal, encompassing both coastal and inland dynamics, are emblematic of the region's resilience and adaptability. The diversity of crops, cultivation methodologies, and the unique case of the Douro Valley collectively contribute to a rich tapestry, underscoring the intricate relationship between agriculture, culture, and the environment in this captivating region.

Table 2: Soil Composition (mean ± sd) of Northern Portugal: Coastal vs Inland Regions

Region	**Soil organic carbon (%)**	**Sand fraction (%)**	**Clay fraction (%)**	**Slope (%)**
coastal	0.86 ± 0.76	4.76 ± 2.23	21.44 ± 2.53	6.14 ± 3.10
inland	0.26 ± 0.54	3.26 ± 1.48	22.21 ± 3.09	5.79 ± 2.30

The diverse soil compositions between the coastal and inland regions of Northern Portugal play a pivotal role in shaping agricultural practices and influencing the sustainability of farming endeavors. Examining key parameters such as Soil Organic Carbon (SOC), sand fraction, clay fraction, and slope provides valuable insights into the unique characteristics of these regions.

In the coastal region, characterized by an average SOC content of 0.86%, the soil exhibits a higher concentration of organic matter. This organic richness enhances fertility and water retention, contributing to favorable conditions for crop cultivation (Lal, 2008). The higher sand fraction (4.76%) in coastal soils promotes effective drainage and aeration, mitigating waterlogging issues and allowing for optimal root development (Lal, 2008). Additionally, the moderate averaged slope (6.14%) facilitates water runoff, preventing stagnation that could lead to soil erosion.

Conversely, the inland region displays distinct soil attributes. With an average SOC of 0.26%, the soil in this area has a lower organic matter content. This variance can impact nutrient availability and water retention, necessitating targeted agricultural practices(Moges and Holden, 2008). The slightly lower sand fraction (3.26%) implies reduced drainage efficiency, requiring careful water management strategies to prevent waterlogging. The higher clay fraction (22.21%) enhances water retention but may pose challenges related to drainage.

The differences in soil composition between these regions are influenced by a multitude of factors, including climate, vegetation, and geological processes. Coastal soils benefit from marine-derived organic matter, contributing to their higher SOC content (Korobushki, 2022). In contrast, inland areas may undergo different weathering processes affecting clay content (Moges and Holden, 2008). Understanding these soil nuances is crucial for tailoring agricultural practices that optimize productivity and minimize environmental impact. Farmers along the coast can leverage the organic-rich soil for diverse crops, while those inland may need to implement specific soil amendments to enhance fertility. Strategic irrigation practices, crop selection, and erosion control measures can be customized based on these soil characteristics, ensuring a sustainable approach that aligns with the inherent qualities of each region. As Northern Portugal faces the imperative of sustainable agriculture, acknowledging and working with these soil variations becomes instrumental in fostering resilient and environmentally conscious farming practices.

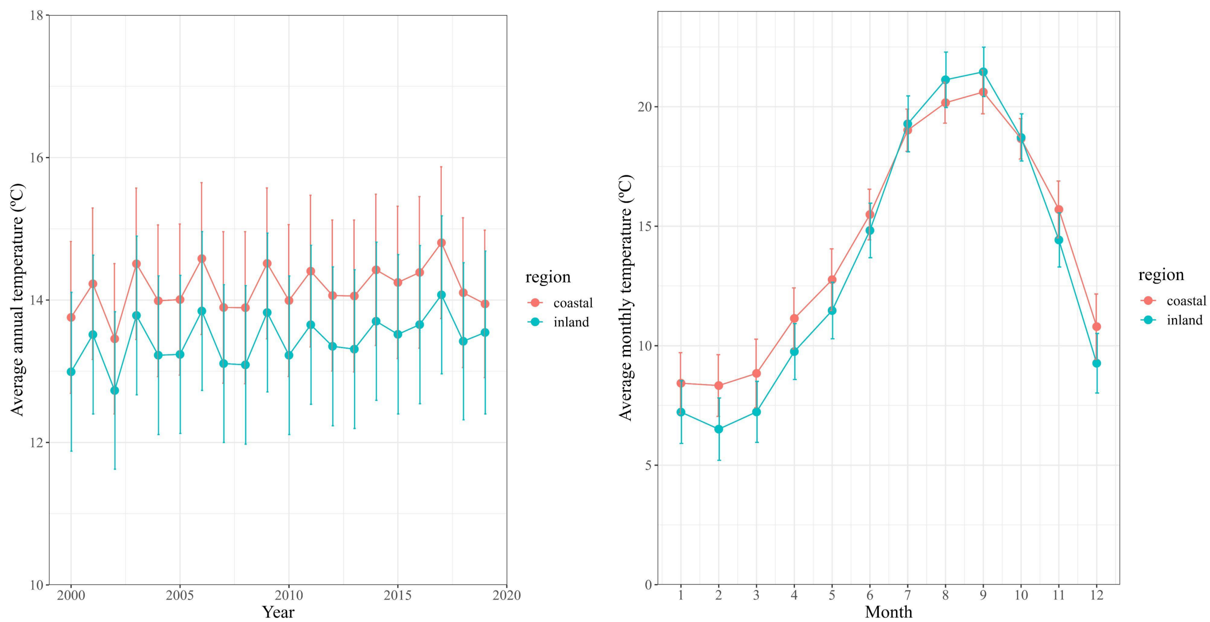

Figure 1: Average annual and monthly temperatures in the coastal and inland regions of Northern Portugal

In dissecting the climatic nuances between the coastal and inland regions of Northern Portugal, a comprehensive understanding of the meteorological variables reveals distinctive patterns that significantly influence agricultural practices. As we explore the climatic disparities, it becomes evident that the coastal areas, influenced by the temperate Atlantic Ocean, exhibit a milder overall climate compared to the inland expanses (Mora, 2020). One crucial aspect is the annual temperature, where empirical evidence indicates that the coast experiences a higher average temperature throughout the year compared to the inland regions. Graphical representations affirm this trend, showcasing the coastal region's thermal moderation attributed to the maritime influence. This climatic advantage translates into a more temperate environment, influencing the types of crops that thrive along the coast. However, delving deeper into the temperature dynamics, the inland areas exhibit a more pronounced oscillation between seasons. The graphs elucidate the inland's colder winter months and hotter summer months, unveiling a more extreme temperature range. This climatic characteristic can significantly impact agricultural practices, influencing crop choices and the timing of planting and harvesting.

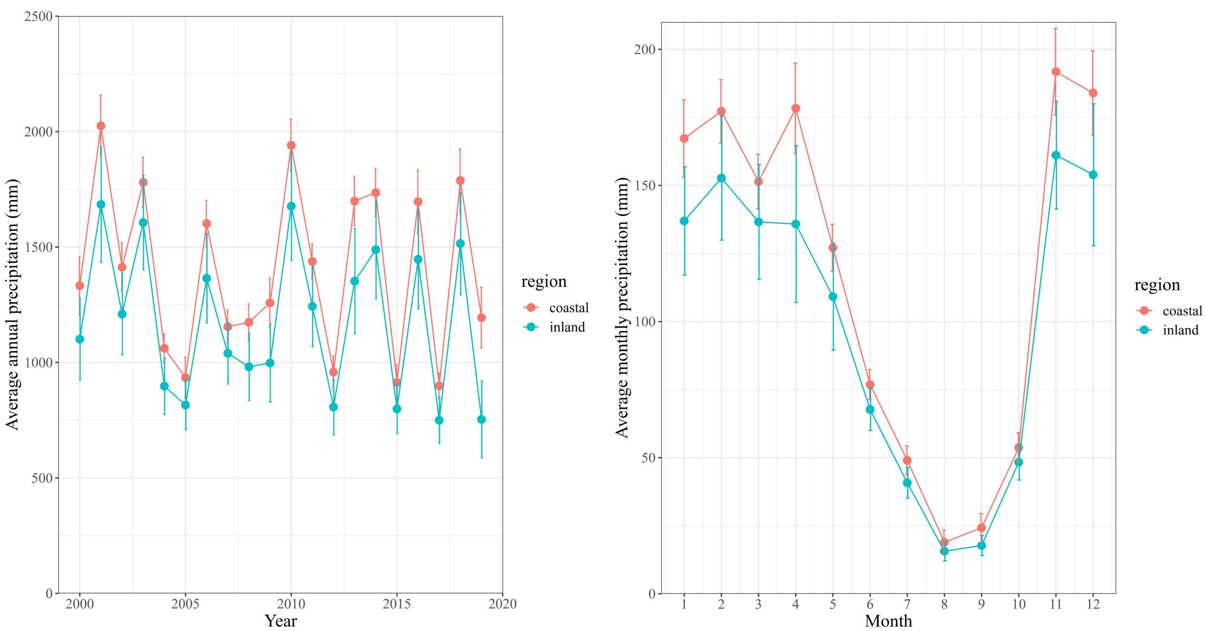

Figure 2: Average annual and monthly precipitation in the coast and inland regions of Northern Portugal

Precipitation patterns further underscore the climatic divergence. On an annual scale, the coastal regions emerge as recipients of slightly more rainfall, a testament to the oceanic moisture-laden air masses that prevail (Mora,2020). Monthly precipitation graphs reinforce this trend, illustrating that not only does the coast receive more annual rainfall, but the precipitation is distributed more evenly throughout the year. This consistent moisture supply can be advantageous for crops, providing a stable water source. Conversely, the inland areas, experiencing a more continental climate, contend with lower annual precipitation and lower average monthly precipitation. This climatic characteristic introduces challenges for agriculture, necessitating strategic water management practices to mitigate the impact of drier periods.

In summary, the climatic disparities between the coastal and inland regions of Northern Portugal play a pivotal role in shaping agricultural practices. The coast's milder temperatures and more consistent rainfall provide a conducive environment for certain crops, fostering a diverse agrarian landscape. On the other hand, the inland's more extreme temperature fluctuations and variable precipitation necessitate adaptive agricultural strategies to navigate the challenges posed by a less predictable climate. This intricate interplay between climate and agriculture highlights the need for region-specific approaches to ensure the sustainability and resilience of Northern Portugal's agricultural sector.

3. Methods

3.1 Introduction of Indicators

The assessment of agricultural sustainability in both the inland and coastal regions of Northern Portugal will be anchored in key indicators that provide insights into environmental, economic, and productivity aspects. These indicators, namely Nitrogen (N) surplus, Irrigation, and soil erosion predictions for 2019 and also for 2070 based on Representative Concentration Pathways (RCP) 2.6 and RCP 8.5, agricultural gross domestic product, and crop yield are integral to understanding the overall impact of current agricultural practices. Data sources for each indicator are displayed in Table 3.

Table 3: Sustainability Indicators and Sources

Indicator	**Unit**	**Temporal and spatial resolution**	**Source**
Nitrogen surplus	kg N/(ha.yr)	Annual (2010-2019); Municipality level	Serra et al. (2023)
Irrigation	m3/yr	Annual (2010-2019); Municipality level	
Soil erosion	tonnes/ha	Annual (2019 and 2070); 100m x 100m	Borrelli et al. (2022)
Agricultural gross domestic product	million USD	Annual (2015); 10km x 10km	Ru et al. (2023)
Crop yield	tonnes/ha	Annual (2010-2019); Municipality level	Statistics Portugal (2023)

The Nitrogen surplus indicator will serve as a proxy of agricultural pollution as well as a measure of the efficiency of nitrogen use within agricultural systems (Mohanty et al. 2020,). A surplus of nitrogen impacts both terrestrial and aquatic ecosystems. On a field scale, empirical investigations have firmly established a positive correlation between nitrogen surplus and emissions of N2O, NO3–leaching, and NH3 volatilization (Boaers, 1996). Even when accounting for trade-off effects, such as CH4 emissions originating from cattle and manure storage, a distinct positive relationship persists between nitrogen surplus at the farm gate and the overall emission of greenhouse gases (Groenigen et al., 2008). By evaluating N surplus, the paper aims to shed light on the environmental implications of current agricultural practices in terms of nitrogen management and greenhouse gas emissions.

Irrigation practices play a pivotal role in water resource utilization and sustainability. Excessive irrigation can lead to extensive water use, affecting both the quantity and quality of available water resources (Stockle, 2002). The irrigation sector has exerted considerable environmental stress for a long time now. The substantial withdrawal of water for irrigation purposes leads to an inadequate supply of water in rivers and wetlands, negatively impacting ecosystems that rely on this water resource (Azad et al, 2014).

Soil erosion predicted using the Revised-Universal-Soil-Loss-Equation-based Global Soil Erosion Modelling for 2019 and 2070 based on the Representative Concentration Pathways (RCP) 2.6 and RCP 8.5, will be a key focus for evaluating the resilience of agricultural landscapes. The RCPs represent the radiative forcing values, in this case, 2.6 and 8.5 W m^{-2}.

Soil erosion not only affects productivity by depleting fertile topsoil but also contributes to sedimentation in water bodies, impacting aquatic ecosystems. Historically, researchers initially overlooked climate scenario-driven forecasts related to soil erosion (Mullan et al., 2012). Soil erosion, as a consequence of current climate fluctuations, poses a significant threat to the environment, agricultural output, global food security, and livelihoods (Pandey et al., 2016; Lal, 2014). Therefore, it is crucial to explore the effects of climate variations on the hazards of soil erosion and anticipate its vulnerability. This understanding is essential for implementing effective measures to safeguard valuable natural resources. This indicator will provide valuable insights into the susceptibility of the regions to erosion under different climate scenarios, thereby addressing concerns related to land degradation and long-term agricultural viability.

Agricultural Gross Domestic Product (GDP) stands as a pivotal indicator when assessing agricultural practices in Northern Portugal, acting as a vital metric for the primary sector upon which the livelihoods of over 2.5 billion people hinge (FAO, 2021). Its significance extends beyond mere economic considerations, playing a central role in providing a key source of income for entire households (FAO, 2021). This economic cornerstone is indispensable for understanding patterns and gauging the productivity of economic development within the agricultural sector (Ru et al., 2023). Measuring the overall economic output of the agricultural sector, offers valuable insights into the region's economic health, providing a comprehensive view of the sector's contribution to the overall economy. Examining Agricultural GDP enables policymakers and stakeholders to make informed decisions, guiding sustainable practices that ensure economic viability while aligning with environmental and social objectives (Ru et al., 2023). In Northern Portugal, where agriculture plays an important role in shaping rural communities and livelihoods, the Agricultural GDP becomes a critical barometer. It reflects not only the economic well-being of the sector but also its resilience and adaptability to changing environmental and market conditions. The indicator is particularly insightful in evaluating the effectiveness of sustainable agricultural approaches, as it encapsulates the broader economic implications of these practices on local communities and the region as a whole.

Crop yield serves as a pivotal indicator when assessing the sustainability of agricultural practices in Northern Portugal, mirroring the region's intricate relationship between farming methods, food supply, and economic stability. The importance of crop yield as a sustainability metric is underscored by its direct correlation with food security and resource use efficiency (Kp, 2018). In a region deeply influenced by its food culture, understanding the patterns and productivity of agricultural development through crop yield becomes paramount. The sustainability of crop yield is crucial for ensuring the longevity and continuity of agricultural systems, especially in a context where environmental factors, ecogeography, and crop choices intertwine. Continuous cultivation of the same crops over time can lead to nutrient depletion in the soil, impacting soil productivity and challenging the persistence of specific crops or cropping systems (Kp,2018). Sustainable land management requires a holistic consideration of various pillars of sustainability, including productivity, security, protection, viability, and acceptability.

3.2 Statistical analysis

In the statistical analysis of the indicators, a crucial step involved assessing the normality of the data. Histograms were constructed to visualize the distribution of each dataset, revealing a skewed and non-normal pattern for all indicators (Fig.3). Subsequently, to explore statistically significant differences between the coastal and inland regions of Northern Portugal, a Kruskal-Wallis test was employed. This non-parametric test was selected due to the non-normal distribution of the data. The Kruskal-Wallis test allows for the comparison of medians across different groups, providing valuable insights when the assumption of normality is not met (Laerd Statics, 2018). The obtained p-values from the Kruskal-Wallis test enabled the determination of whether there were significant differences in the indicators between the two regions. A noteworthy outcome was the rejection of the null hypothesis for certain indicators, indicating substantial distinctions in agricultural practices between the coastal and inland areas. This robust statistical approach ensures the reliability and validity of the findings, contributing to a comprehensive understanding of the sustainability dynamics in Northern Portugal.

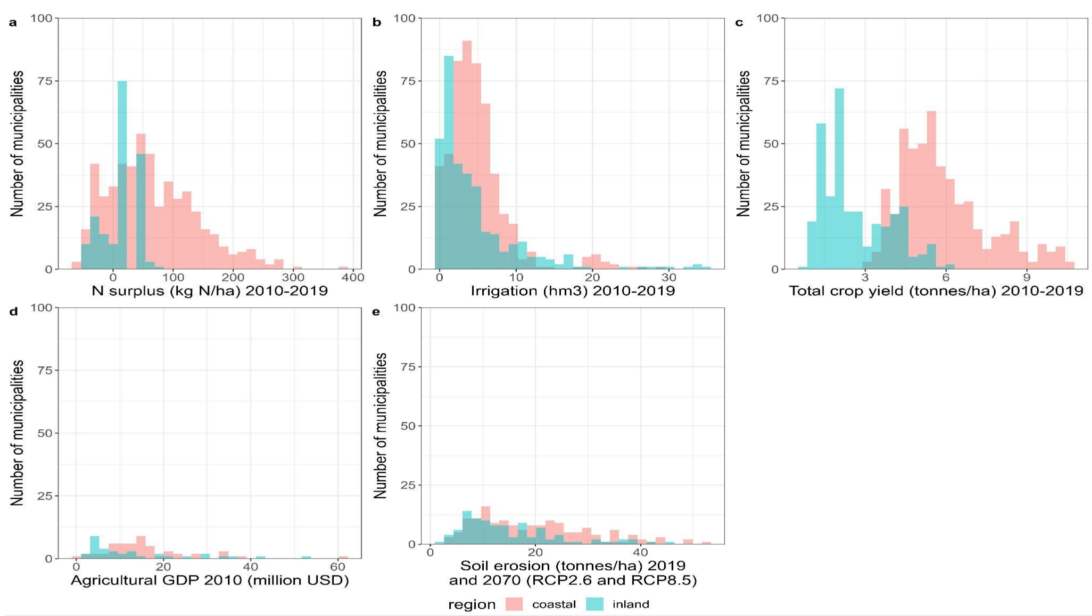

Figure 3: Histograms for coastal and inland regions of Northern Portugal for the different indicators.

4. Results and Discussion

4.1 Exploring the differences between the coastal and inland regions of Northern Portugal

4.1.1 Soil Erosion

The assessment of soil erosion rates in both the coastal and inland regions of Northern Portugal reveals notable disparities with significant implications for agricultural practices and environmental sustainability. In 2019, the coastal region exhibited a higher average soil erosion rate of 16±10 tonnes/ha (average±SD) compared to the inland's rate of 14±8 tonnes/ha (Fg.4). The statistical analysis indicates a statistically significant difference ($p=0.0003053$), emphasizing the distinct erosion dynamics between the two regions. Soil erosion is a multifaceted phenomenon influenced by factors such as soil characteristics, terrain slope, vegetation cover, and the quantity and intensity of rainfall (Montgomery, 2007).

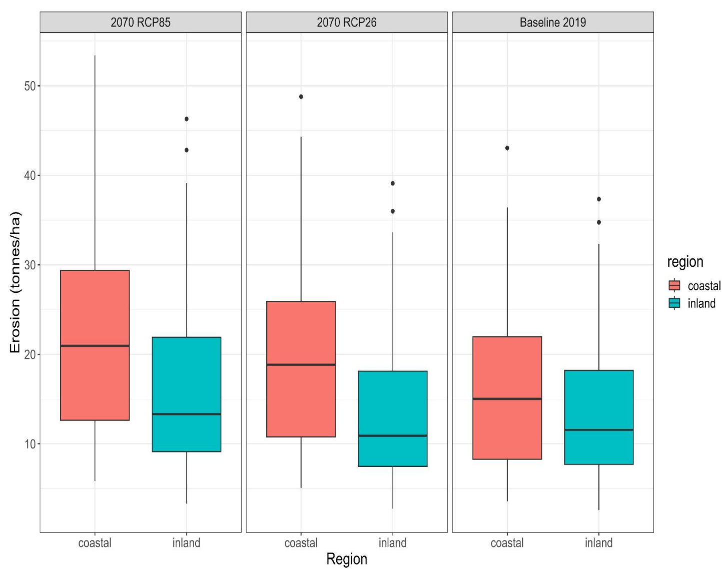

Figure 4: Temporal variation of soil erosion by water (for 2019 and 2070) in the coastal and inland regions of Northern Portugal.

Looking ahead to 2070, the predictions under RCP 2.6 and RCP 8.5 suggest a concerning increase in soil erosion rates for both regions, with the coastal average projected to be 21±11 tonnes/ha and the inland at 15±10 tonnes/ha. These forecasts signal a potential escalation in soil erosion if current agricultural practices remain the same.

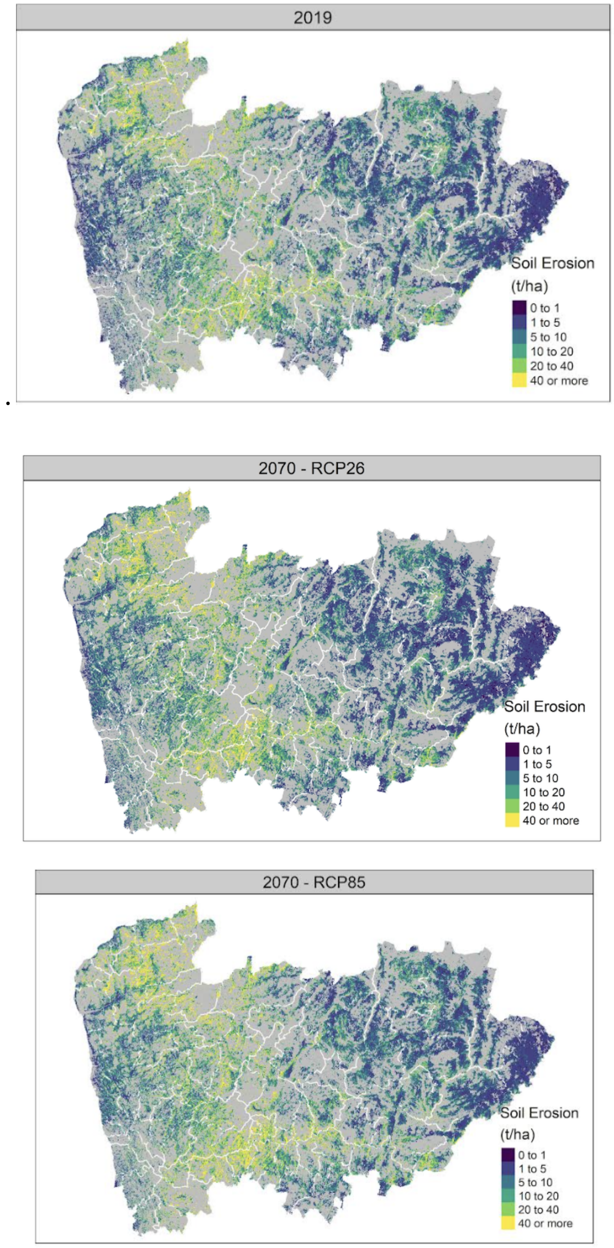

Figure 5: Spatial variation of soil erosion by water in 2019 (top) and 2070 from RCP26 (middle) and RCP85 (bottom) scenarios.

Despite the higher erosion rates along the coast, the inland's heavy reliance on viticulture raises concerns about the reliance on viticulture in the region and its sustainability. The data aligns with existing research highlighting soil erosion as a critical threat to soil health, contributing to yield decline, ecosystem degradation, and economic repercussions (Borrelli et al., 2022). Particularly, vineyards, a cornerstone of inland agriculture, are identified as a major contributor to soil loss, emphasizing the need for sustainable viticulture practices (Prosdocimi et al., 2016). The positive relationship between erosion rate and mean rainfall intensity underscores the influence of precipitation patterns on erosion(Borrelli et al., 2022). Both regions are characterized by Mediterranean climates where high-intensity rainfall events happen during the winter months (Fig.2). Addressing soil erosion rates is crucial to preserving the long-term viability of agriculture and safeguarding the environmental health of both the coastal and inland regions of northern Portugal.

4.1.2 Nitrogen Surplus

The nitrogen surplus (Fig. 6) reveals distinct patterns between the coastal and inland regions of Northern Portugal. The average nitrogen surplus over the period from 2010 to 2019 was notably higher along the coast, with an average of 65 ± 74 kg N/ha (average ± SD). In contrast, the inland regions exhibited a lower nitrogen surplus, averaging 21 ± 22 kg N/ha over the same timeframe. Figure 6 shows that the nitrogen surplus peaked at almost 400 kg N/ha in the coastal regions, which is more than four times higher than the peak attained in the inland regions. This difference in magnitude points to a marked variation in terms of nitrogen hotspots in agricultural systems across Northern Portugal. Indeed, the inland regions are known nitrogen hotspots caused by intensive crop-livestock systems with a large surplus of manure relative to crop nitrogen demand (Serra et al., 2023). A statistically significant difference was found between the coastal and inland regions per the Kruskal-Wallis test ($p \sim 0$).

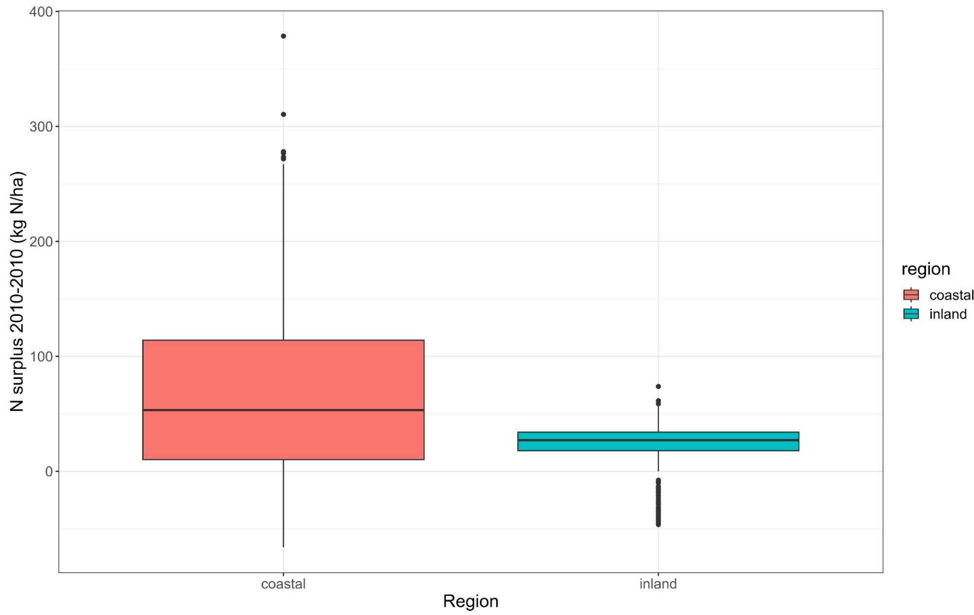

Figure 6:Temporal variations of N surplus (from 2010-2019) in the coastal and inland regions of Northern Portugal

The environmental implications of such nitrogen surpluses are noteworthy. In the atmosphere, ammonia (NH3) emissions, a byproduct of nitrogen surplus, may be oxidized to nitrous oxide (N2O), a potent greenhouse gas associated with global warming and ozone layer depletion (Banerjee, 2001). This emphasizes the urgency of improving agricultural nitrogen management to produce more nutritious food for a growing global population while simultaneously maintaining or enhancing soil fertility and mitigating adverse environmental impacts (Zhang et al., 2019). The observed differences in nitrogen surplus between coastal and inland areas may also be influenced by variations in annual average temperatures and rainfall, further highlighting the complex interplay of climatic factors in shaping nitrogen losses and agricultural sustainability in these distinct regions (Zhang et al., 2019).

Considering the higher nitrogen surplus along the coast, there is a likelihood of elevated environmental impacts, particularly concerning greenhouse gas emissions and potential contributions to global warming and ozone layer destruction. The coastal regions' intensive farming practices may result in increased ammonia emissions, emphasizing the need for targeted nitrogen management strategies to curtail environmental repercussions. In contrast, the inland regions, despite exhibiting a lower nitrogen surplus, still require careful management to address the localized challenges posed by nitrogen hotspots in crop livestock systems. The disparities in nitrogen surplus underscore the importance of region-specific considerations in devising sustainable agricultural practices that balance productivity with environmental conservation.

4.1.3 Irrigation

The investigation into irrigation practices in Northern Portugal has provided noteworthy insights into regional water consumption (Fig.7). Calculating the averages based on the available data revealed that, on average, the coastal region utilized approximately $4985 \pm 4294 hm^3/yr$ of water for irrigation, whereas the inland region demonstrated a slightly lower average of $4704 \pm 5881\ hm^3/yr$. Despite the lower average, the inland regions attained higher peaks in irrigation water consumption (up to 35 hm^3/yr) in municipalities where irrigated maize is grown for exports or livestock feed. In these municipalities, maize fields are sometimes irrigated up to roughly 700 mm/yr. Since agricultural systems in the coastal regions are less intensively managed, these results not only in less nitrogen pollution (Fig.6) but also in smaller irrigation amounts (Fig. 7). Both regions are characterized by drip-fed vineyards, which consume up to 200-350mm/yr (Serra et al., 2023).

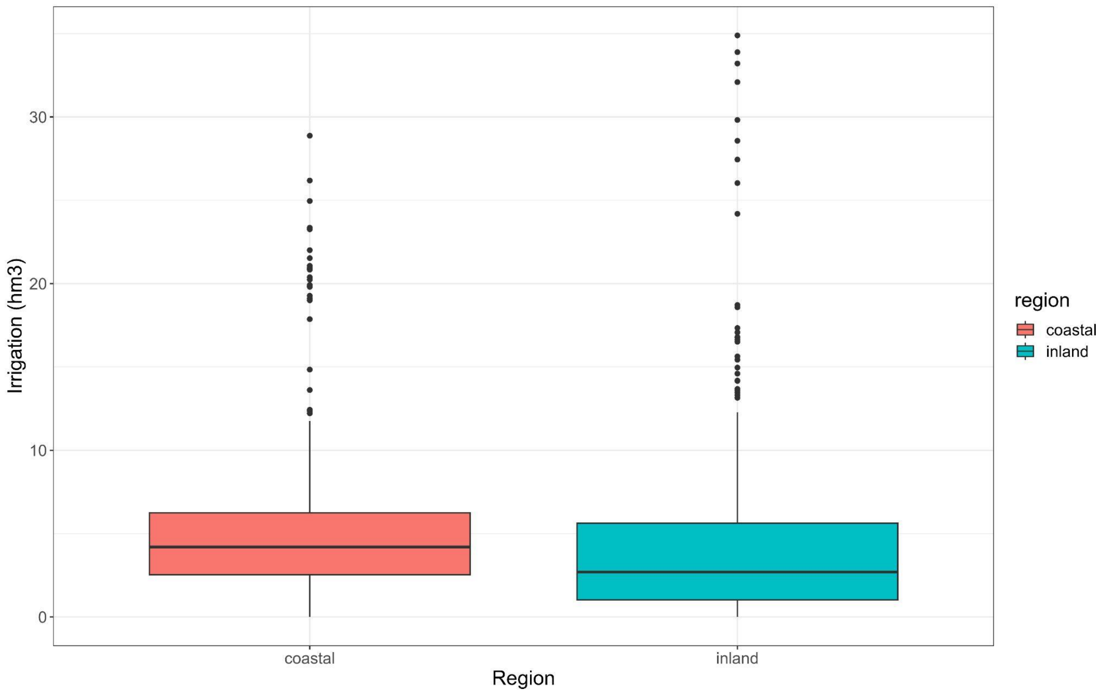

Figure 7: Temporal variations of the rate of irrigation (2010-2019) in the coastal and inland regions of Northern Portugal

The resulting exceptionally low p-value of 3.064 e -06 signifies statistical significance between the rates of irrigation in the two regions. The rates of irrigation in each region have profound implications for the environmental impact of agricultural practices. Crops with high water and nitrogen requirements, particularly in the inland regions, pose an increased risk of nitrate pollution to groundwater (Stockle, 2001). Farmers' tendency to over-irrigate exacerbates these issues, as the incentive to use more water for enhanced production clashes with society's opposing incentive to reduce water use and mitigate potential negative environmental impacts (Khan and Hanjra, 2007). The observed differences in irrigation rates underscore the need for targeted water resource management strategies, considering the potential environmental consequences associated with excessive water use in intensive agricultural practices.

4.1.4 Agricultural GDP

The examination of Agricultural Gross Domestic Product (GDP) in Northern Portugal has unveiled economic distinctions between the coastal and inland regions, shedding light on the intricate dynamics of each area (Fig.8). Averaging the available data shows that, on average, the coastal region had a GDP of approximately 16 ± 11 million in 2010, slightly surpassing the inland region with a lower average of 14 ± 13 million. Significantly, the coastal region experienced a notable peak GDP of around 62 million in Barcelos, surpassing any production in the inland municipalities. This highlights a higher economic dependency on agriculture in the coastal areas, particularly in thriving municipalities. The standard deviation values reveal considerable variability within each region, reflecting diverse economic landscapes.

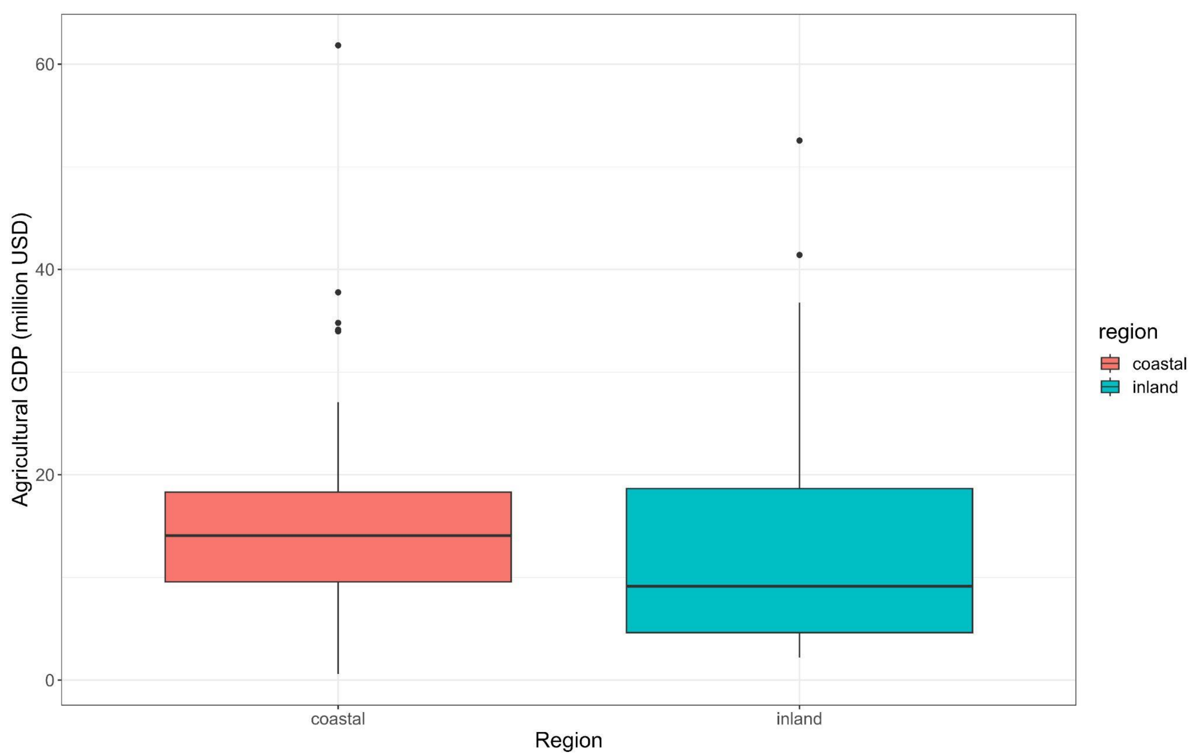

Figure 8: Temporal variations of Agricultural GDP (in 2015) in the coastal and inland regions of Northern Portugal

Despite the statistical insignificance with a p-value of 0.0788, a closer examination unveils economic nuances and dependencies linked to agriculture in both coastal and inland regions. Coastal regions, with more export-diverse farming systems, including products like wine, feed crops, and animal and dairy products, contribute to a higher GDP. This export diversity and higher GDP might offer them an advantage in adapting to various conditions arising from climate change, although it also exposes them to greater risks because they have more to lose. Intriguingly, the absence of significant differences in GDP suggests that the observed excessive nitrogen pollution, erosion, and irrigation in the coastal region may not necessarily have a direct translation into economic output.

This finding underscores the complexity of the relationship between agricultural practices, environmental factors, and economic outcomes in Northern Portugal. It emphasizes the need for further research to unravel the intricate dynamics shaping the region's agricultural landscape. This holistic understanding is essential for devising sustainable practices that not only optimize economic outcomes but also mitigate environmental impacts, ensuring the resilience and long-term viability of Northern Portugal's agriculture.

4.1.5 Crop Yield

The analysis of crop yield data spanning from 2010 to 2019 in Northern Portugal unveils substantial distinctions between the coastal and inland regions, offering valuable insights into regional agricultural productivity (Fig.9). Averaging the data highlights a significantly higher average crop yield of 6 tonnes/ha along the coast, in stark contrast to the inland region's average yield of 3 tonnes/ha. The standard deviation calculations reveal variability within each dataset, with the coastal region exhibiting a standard deviation of 2 tonnes/ha, indicative of notable fluctuation in crop yields. Conversely, the inland region displays a lower standard deviation of 1 tonne/ha, suggesting a comparatively more stable yield pattern. The resulting p-value, < 2.2 e-16, signifies an exceptionally high level of significance.

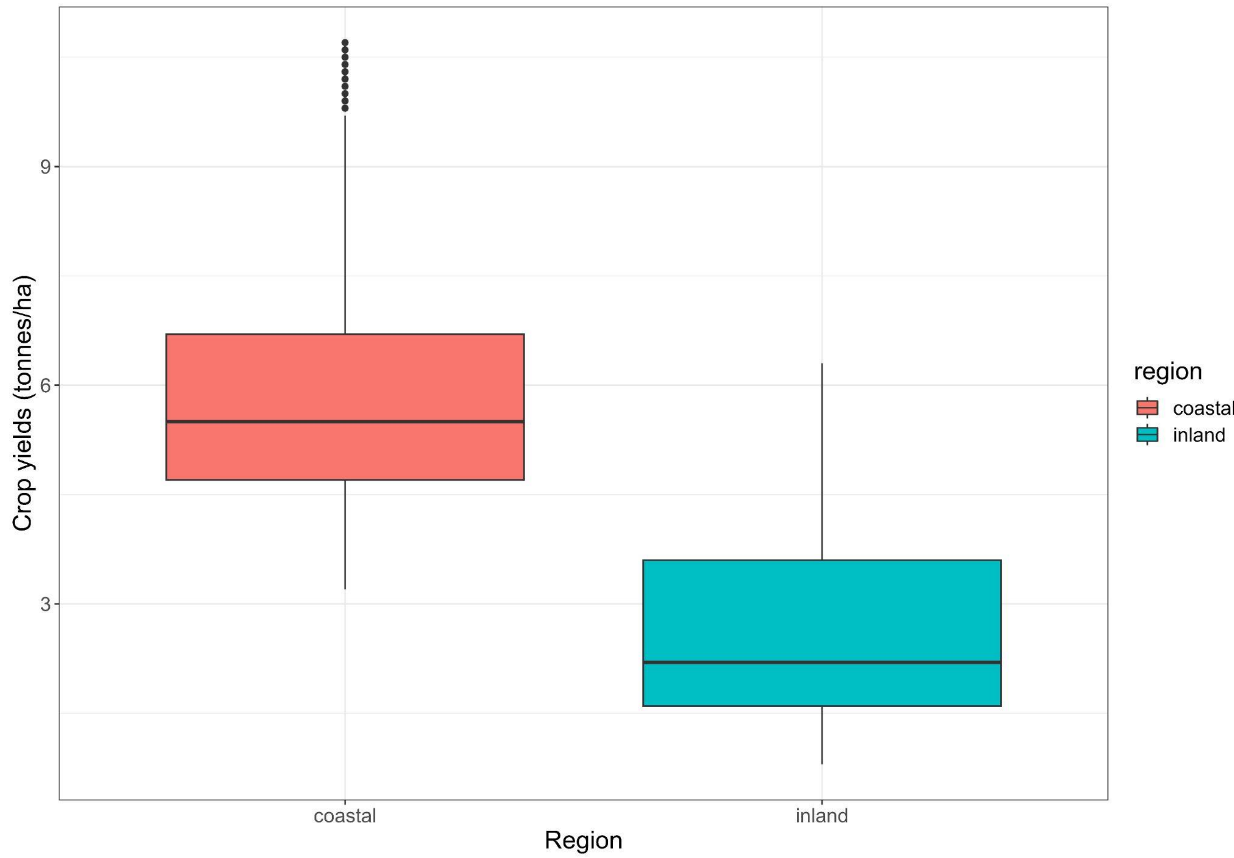

Figure 9: Temporal variations of crop yields (from 2010-2019) in the coastal and inland regions of Northern Portugal

Furthermore, the coastal region's significantly higher maximum yield of around 10 tonnes/ha emphasizes the potential for elevated agricultural productivity in these areas. This disparity in maximum yield suggests that coastal regions may have certain advantages or optimized practices leading to more bountiful harvests. The higher crop yield in coastal areas may be attributed to a combination of factors such as favorable climate, soil conditions, and potentially advanced farming techniques (Korobushkin, et al., 2022). However, it also raises questions about the sustainability of such high yields over long periods which are associated with intensive agricultural practices that result in environmental degradation (Fangueiro et al., 2022). The higher crop yield in the coastal region correlates with the higher nitrogen surplus due to increased fertilizer use and livestock density thus resulting in more agricultural pollution in the region (Fangueiro et al., 2008). This observed variability in crop yields highlights the need for region-specific agricultural strategies that balance productivity with environmental conservation, ensuring the long-term sustainability of farming practices.

4.2 Suggestions of Sustainable Agricultural Practices

In the coastal region, characterized by a higher agricultural GDP and economic dependencies on agriculture, a strategic focus on sustainability is imperative (Fig.8). The integration of sustainable practices is not only an environmental necessity but also aligns with the economic robustness of the coastal agriculture sector. The coastal region's high dependency on livestock presents a unique opportunity for the integration of crop-livestock farming. By combining crop cultivation with livestock management, the coastal area can enhance soil fertility by taking the nitrogen output from livestock and redirecting it as an input for crop production. Despite potential challenges, the economic strength of the coastal region positions it favorably to navigate and invest in the long-term benefits of integrated crop-livestock farming (Table 4). Given the region's emphasis on export-diverse crops, organic farming becomes a strategic choice for reducing nitrogen surplus. The coastal agriculture sector's higher GDP provides the financial flexibility to invest in organic farming practices, contributing to the reduction of nitrogen pollution and fostering a more environmentally sustainable model (Fig.8). Intercropping, especially with legumes, offers a dynamic strategy for the coastal region to enhance soil fertility and reduce the need for synthetic nitrogen fertilizers(Table 4). Legumes, known for their nitrogen-fixing capabilities, can enrich the soil with essential nutrients (Liu et al., 2011). Despite potential challenges related to yield reduction of the main crop and maintenance costs, the advantages in terms of increased biodiversity and minimized environmental impact position intercropping as a strategic choice for the coastal agriculture sector (Table 4).

The inland regions of Northern Portugal present distinct challenges, necessitating a nuanced approach to sustainable agriculture. Unlike coastal areas, challenges here are not solely rooted in agricultural management practices; they encompass water scarcity, rural isolation, and heightened vulnerability to climate change. Tailoring sustainable practices to these specific challenges is crucial for the resilience and prosperity of inland agriculture. While drip irrigation is already prevalent in the inland region, the challenge lies in the context of water scarcity and availability. The region's high peak irrigation consumption, coupled with the potential impacts of climate change, emphasizes the need for more water-efficient irrigation systems (Fig.7). Enhancing the efficiency of existing drip irrigation infrastructure, coupled with the exploration of innovations like smart irrigation technologies, would be useful (Table 4).

Inland regions, being more rural and distant from essential infrastructure, require strategies that go beyond the field. Building resilient agricultural communities involves investing in local infrastructure, such as road networks connecting farms and facilitating transportation to markets. Strengthening community support systems and agricultural cooperatives can foster knowledge exchange and resource-sharing, addressing the inherent challenges of rural isolation. Inland regions also face unique challenges related to soil erosion resulting from cultural terraced vineyards. Implementing climate-resilient terrace farming practices, such as contour plowing and cover cropping, can mitigate erosion risks (Pijl et al.,2021). This involves integrating traditional practices with modern techniques, ensuring sustainable land management that adapts to changing climatic conditions. The distance from seaports and airports poses a challenge to accessing agricultural markets for inland farmers. Implementing strategies to improve market access, such as the development of local processing facilities and the establishment of regional distribution networks, can overcome logistical barriers. Embracing digital platforms for marketing and sales can also open new avenues for inland farmers to connect with a broader consumer base.

Table 4: Sustainable agricultural practices

	Intercropping	Organic Farming	Agroforestry	Integrated Crop-Livestock	Precision Irrigation
Definitions	The cultivation of multiple crops either simultaneously or successively throughout a substantial portion of their growth cycle within a specific land management unit.	Crops are grown using organic wastes and compost as fertilizer. Pests and weeds are exterminated using birds and insects. No synthetic fertilizer or chemicals are used in production	Integration of trees and shrubs into agricultural practices, combining forestry and agricultural practices in a way that brings ecological and economic benefits	Agricultural approach that combines the cultivation of crops with livestock farming on the same piece of land	An advanced agricultural irrigation method that involves the precise application of water s directly to the roots of crops through a network of buried driplines
Advantages	Maximize water efficiency, improve soil fertility, minimize soil erosion, increase production, increase pest and disease control, and increase biodiversity	Improved soil fertility, reduced greenhouse gas emissions, natural pest control, Nutrient-rich food produced, more energy efficient, and reduction of water pollution	Biodiversity enhancement, improved soil health, diversification of income source, climate change mitigation, water conservation, reduced fertilizer and pesticide use, enhanced crop yield	Enhanced nutrient cycling, diversified income source, improved soil structure, natural weed and pest control, and efficient use of land, water and nutrients	More efficient water use, less water quality hazards, greater water application uniformity, improved plant health, weed control, and decreased energy cost
Disadvantages	Yield reduction of main crop, maintenance cost, damages to other crops while harvesting one crop, and competition for resources between crops	High production costs, vulnerable to pest and disease, and labor-intensive farming	Land use competition, complex management, delayed benefits, limited crop choice, initial investment, and risk if pest and disease spread	Potential disease transmission, infrastructure investment, managing complexity, and crop yield reductions,	Difficulty monitoring and evaluating irrigation events, high initial investment, increased maintenance, and Emitter discharge rates may exceed redistribution

					capacity
Sources	Definition: Beillouin (2021) Advantages: Mousavi and Eskandari (2011) Disadvantages: Gebru (2015)	Muscanescu (2013)	Nath et al. (2015)	Definition:Moraine (2017) Advantages and Disadvantages: Nie (2013)	Lamm (2002)

5. Conclusion

The comprehensive assessment of agricultural systems in Northern Portugal's coastal and inland regions, as revealed through key indicators, underscores the necessity for a tailored and bottom-up approach to the implementation of sustainable practices. Although the indicators present some limitations in terms of data accuracy and spatial resolution, these nonetheless allowed me to gain insight into each region's unique characteristics, advantages, and challenges demand nuanced strategies that harmonize environmental resilience with economic viability. The inland regions, distinct in their agricultural challenges, showcase lower nitrogen surplus, higher soil erosion rates, and high peak irrigation consumption but with a lower return in terms of agricultural output, both in terms of yields and GDP. The rural nature of inland areas demands a holistic strategy that not only sustains agriculture but also nurtures resilient and interconnected farming communities. The coastal regions, marked by higher agricultural GDP, higher nitrogen surplus, and a fairly moderate climate show promise for the integration of certain sustainable agriculture practices. Crop-livestock farming, Intercropping, and organic farming all are agricultural practices the coastal region could benefit from utilizing. Despite potential challenges, such as yield reduction and maintenance costs, the economic strength of the coastal region positions it favorably to embrace these sustainable practices. By embracing the strengths, mitigating the challenges, and adapting to the climatic variations of each region, Northern

Portugal can foster a resilient, productive, and environmentally conscious agricultural landscape for generations to come.

References

Arora, N. K. (2019). Impact of climate change on agriculture production and its sustainable solutions. *Environmental Sustainability*, *2*(2), 95–96. https://doi.org/10.1007/s42398-019-00078-w

Azad, A. S., Ancev, T., & Hernández-Sancho, F. (2014). Efficient water use for sustainable irrigation industry. *Water Resources Management*, *29*(5), 1683–1696. https://doi.org/10.1007/s11269-014-0904-8

Bai, Z. (2008). *Global assessment of land degradation and improvement: 1. Identification by remote sensing*. Research@WUR. https://research.wur.nl/en/publications/global-assessment-of-land-degradation-and-improvement-1-identific

Banerjee, B., Pathak, H., & Aggarwal, P. (2002). Effects of dicyandiamide, farmyard manure and irrigation on crop yields and ammonia volatilization from an alluvial soil under a rice (Oryza sativa L.)-wheat (Triticum aestivum L.) cropping system. *Biology and Fertility of Soils*, *36*(3), 207–214. https://doi.org/10.1007/s00374-002-0528-7

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, *5*(1). https://doi.org/10.1038/sdata.2018.214

Beillouin, D., Ben-Ari, T., Malézieux, É., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology*, *27*(19), 4697–4710. https://doi.org/10.1111/gcb.15747

Boers, P. (1996). Nutrient emissions from agriculture in the netherlands, causes and remedies. *Water Science and Technology*, *33*(4–5). https://doi.org/10.1016/0273-1223(96)00229-6

Borrelli, P., Ballabio, C., Yang, J. E., Robinson, D. A., & Panagos, P. (2022). GloSEM: High-resolution global estimates of present and future soil displacement in croplands by water erosion. *Scientific Data*, *9*(1). https://doi.org/10.1038/s41597-022-01489-x

Climate: Center in Portugal. (n.d.). Worlddata.info. https://www.worlddata.info/europe/portugal/climate-center.php

De Dios Miranda, J., Armas, C., Padilla, F. M., & Pugnaire, F. I. (2011). Climatic change and rainfall patterns: Effects on semi-arid plant communities of the Iberian Southeast. *Journal of Arid Environments*, *75*(12), 1302–1309. https://doi.org/10.1016/j.jaridenv.2011.04.022

Fangueiro, D., Pereira, J., Coutinho, J., Moreira, N., & Trindade, H. (2008). NPK farm-gate nutrient balances in dairy farms from Northwest Portugal. *European Journal of Agronomy*, *28*(4), 625–634. https://doi.org/10.1016/j.eja.2008.01.007

Figueiredo, T. D., Fonseca, F., & Hernández, Z. (2020). Terraced vineyards of the Douro wine region, Portugal: a soil and water management perspective. *Pirineos*, *175*, e058-e058.

Gebru, H. (2015). A review on the comparative advantages of intercropping to mono-cropping system. *Journal of Biology, Agriculture and Healthcare*, *5*(9), 1-13.

Gomiero, T., Pimentel, D., & Paoletti, M. G. (2011). Is there a need for a more sustainable agriculture? *Critical Reviews in Plant Sciences*, *30*(1–2), 6–23. https://doi.org/10.1080/07352689.2011.553515

Hunter, L. M., Koning, S. M., Fussell, E., King, B., Rishworth, A., Merdjanoff, A., Muttarak, R., Riosmena, F., Simon, D., Skop, E., & Van Den Hoek, J. (2021). Scales and sensitivities in climate vulnerability, displacement, and health. *Population and Environment*, *43*(1), 61–81. https://doi.org/10.1007/s11111-021-00377-7

Joint FAO/WHO Expert Committee on Food Additives. Meeting, & World Health Organization. (2006). *Safety evaluation of certain contaminants in food* (Vol. 82). Food & Agriculture Org..

Khan, S., & Hanjra, M. A. (2008). Sustainable land and water management policies and practices: a pathway to environmental sustainability in large irrigation systems. *Land Degradation & Development*, *19*(5), 469–487. https://doi.org/10.1002/ldr.852

Korobushkin, D. I., Saifutdinov, R. A., Zuev, A. G., & Zaitsev, A. S. (2022). Incorporation of marine organic matter by terrestrial detrital food webs: abiotic vs. biotic vectors. *CATENA*, *211*, 106010. https://doi.org/10.1016/j.catena.2021.106010

Kp, V. (2018). *Crop yield sustainability: A few measures*. https://www.phytojournal.com/special-issue/2018.v7.i2S.4454/crop-yield-sustainability-a-few-measures

Kruskal-Wallis H Test in SPSS Statistics | Procedure, output and interpretation of the output using a relevant example. (n.d.). https://statistics.laerd.com/spss-tutorials/kruskal-wallis-h-test-using-spss-statistics.php

Lal, R. (1991). Soil structure and sustainability. *Journal of Sustainable Agriculture*, *1*(4), 67–92. https://doi.org/10.1300/j064v01n04_06

Lamm, F. R. (2002, December). Advantages and disadvantages of subsurface drip irrigation. In *International Meeting on Advances in Drip/Micro Irrigation, Puerto de La Cruz, Tenerife, Canary Islands* (pp. 1-13)

Liu, Y., Wu, L., Baddeley, J. A., & Watson, C. (2011). Models of biological nitrogen fixation of legumes. In *Springer eBooks* (pp. 883–905). https://doi.org/10.1007/978-94-007-0394-0_39

Moges, A., & Holden, N. M. (2008). Soil fertility in relation to slope position and agricultural land use: A case study of umbulo catchment in southern Ethiopia. *Environmental Management*, *42*(5), 753–763. https://doi.org/10.1007/s00267-008-9157-8

Mohanty, S., Swain, C. K., Kumar, A., & Nayak, A. K. (2019). Nitrogen footprint: a useful indicator of agricultural sustainability. In *Springer eBooks* (pp. 135–156). https://doi.org/10.1007/978-981-13-8660-2_5

Montgomery, D. R. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(33), 13268–13272. https://doi.org/10.1073/pnas.0611508104

Moraine, M., Mélac, P., Ryschawy, J., Duru, M., & Thérond, O. (2017). A participatory method for the design and integrated assessment of crop-livestock systems in farmers' groups. *Ecological Indicators*, *72*, 340–351. https://doi.org/10.1016/j.ecolind.2016.08.012

Mousavi, S. R., & Eskandari, H. (2011). A general overview on intercropping and its advantages in sustainable agriculture. *Journal of Applied Environmental and Biological Sciences*, *1*(11), 482-486.

Muscănescu, A. (2013). Organic versus conventional: advantages and disadvantages of organic farming. *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development*, *13*(1), 253-256.

Pijl, A., Wang, W., Straffelini, E., & Tarolli, P. (2022). Soil and water conservation in terraced and non‐terraced cultivations: an extensive comparison of 50 vineyards. *Land Degradation & Development*, *33*(4), 596–610. https://doi.org/10.1002/ldr.4170

Prosdocimi, M., Cerdà, A., & Tarolli, P. (2016). Soil water erosion on Mediterranean vineyards: A review. *CATENA*, *141*, 1–21. https://doi.org/10.1016/j.catena.2016.02.010

Nath, T. K., Jashimuddin, M., Hasan, M. K., Shahjahan, M., & Pretty, J. (2015). The sustainable intensification of agroforestry in shifting cultivation areas of Bangladesh. *Agroforestry Systems*, *90*(3), 405–416. https://doi.org/10.1007/s10457-015-9863-1

Nie, Z., McLean, T., Clough, A., Tocker, J., Christy, B., Harris, R., Riffkin, P., Clark, S., & McCaskill, M. R. (2016). Benefits, challenges and opportunities of integrated crop-livestock systems and their potential application in the high rainfall zone of southern Australia: A review. *Agriculture, Ecosystems & Environment*, *235*, 17–31. https://doi.org/10.1016/j.agee.2016.10.002

Ramião, J. P., Carvalho-Santos, C., Pinto, R., & Pascoal, C. (2022). Modeling the Effectiveness of Sustainable Agricultural Practices in Reducing Sediments and Nutrient Export from a River Basin. *Water*, *14*(23), 3962. https://doi.org/10.3390/w14233962

Roberts, D. P., & Mattoo, A. K. (2018). Sustainable Agriculture—Enhancing environmental benefits, food nutritional quality and building crop resilience to abiotic and biotic stresses. *Agriculture*, *8*(1), 8. https://doi.org/10.3390/agriculture8010008

Rolim, J., Teixeira, J. L., Catalão, J., & Shahidian, S. (2016). The impacts of climate change on irrigated agriculture in southern Portugal. *Irrigation and Drainage*, *66*(1), 3–18. https://doi.org/10.1002/ird.1996

Ru, Y., Blankespoor, B., Wood‐Sichra, U., Thomas, T. S., You, L., & Kalvelagen, E. (2023). Estimating local agricultural gross domestic product (AgGDP) across the world. *Earth System Science Data*, *15*(3), 1357–1387. https://doi.org/10.5194/essd-15-1357-2023

Schleussner, C., Menke, I., Theokritoff, E., van Maanen, N., & Lanson, A. (2020). Climate impacts in portugal. *Clim Analytics*

Serra, J., Paredes, P., Cordovil, C., Cruz, S., Hutchings, N., & Cameira. (2023). Is irrigation water an overlooked source of nitrogen in agriculture? *Agricultural Water Management*, *278*, 108147. https://doi.org/10.1016/j.agwat.2023.108147

Smil, V. (2002). Food production. In *Elsevier eBooks* (pp. 25–50). https://doi.org/10.1016/b978-012153654-1/50005-2

Statistics Portugal - web portal. (n.d.) https://www.ine.pt/xportal/xmain?xpgid=ine_main&xpid=INE

Stockle, C. (2002). ENVIRONMENTAL IMPACT OF IRRIGATION: a REVIEW. *ResearchGate*. https://www.researchgate.net/publication/252698502_ENVIRONMENTAL_IMPACT_OF_IRRIGATION_A_REVIEW

Sustainability in question. (n.d.). Google Books. https://books.google.pt/books?hl=en&lr=&id=5Po4XHe9EHUC&oi=fnd&pg=PA153&dq=economic+benefits+of+sustainable+agriculture&ots=89eLOFIKDq&sig=HZFWCLfr1lPYUkHNxIH1TJ5DD3s&redir_esc=y#v=onepage&q=economic%20benefits%20of%20sustainable%20agriculture&f=false

Van Groenigen, J., Schils, R., Velthof, G., Kuikman, P., Oudendag, D., & Oenema, O. (2008). Mitigation strategies for greenhouse gas emissions from animal production systems: synergy between measuring and modelling at different scales. *Australian Journal of Experimental Agriculture*, *48*(2), 46. https://doi.org/10.1071/ea07197

Vieira, G., Zêzere, J. L., & Mora, C. (Eds.). (2020). *Landscapes and landforms of Portugal*. Springer.

Yang, C., Fraga, H., Van Ieperen, W., & Santos, J. A. (2017). Assessment of irrigated maize yield response to climate change scenarios in Portugal. *Agricultural Water Management*, *184*, 178–190. https://doi.org/10.1016/j.agwat.2017.02.004

Vicente-Serrano, S. M., Trigo, R. M., López-Moreno, J. I., Liberato, M. L., Lorenzo-Lacruz, J., Beguería, S., ... & El Kenawy, A. (2011). Extreme winter precipitation in the Iberian Peninsula in 2010: anomalies, driving mechanisms and future projections. *Climate Research*, *46*(1), 51-65.

Vieira, G., Zêzere, J. L., & Mora, C. (Eds.). (2020). *Landscapes and landforms of Portugal*. Springer.

Zhang, C., Ju, X., Powlson, D. S., Oenema, O., & Smith, P. (2019). Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China. *Environmental Science & Technology*, *53*(12), 6678–6687. https://doi.org/10.1021/acs.est.8b06383