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Economic Diversification Potential: Insights from Mongolia's Livestock Product Value Chains

Mongolia, endowed with abundant natural resources, faces a critical challenge in reducing its reliance on the mining sector and achieving economic diversification. This study aims to identify the potential for economic diversification by developing the non-mining processing industry. To this end, a Revealed Comparative Advantage (RCA) analysis and value chain mapping were employed. The RCA results highlight the importance of livestock-derived products and recognise the livestock sector as having the best potential for achieving economic diversification. Consequently, the value chain of livestock-derived products was mapped, and key challenges at each stage were identified. The study provides actionable recommendations for developing this value chain. The findings underscore that the value chain of livestock-derived products encounters numerous obstacles that must be addressed to build a competitive sector. Key strategies for addressing the issues throughout the value chain include improving animal health, ensuring compliance with good practices and standards, and enhancing competitiveness through advanced technologies, increased financial and investment support, and improved logistics and infrastructure.

Keywords: Economic diversification, Revealed Comparative Advantage, value chain mapping, livestock-derived products, Mongolia

JEL classifications: Q13, Q17.

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Introduction

Economic diversification remains a key component of development strategies for many countries, particularly resource-rich economies like Mongolia. While natural resources significantly contribute to economic growth and improve the livelihoods of local people, extensive research highlights the risks of heavy reliance on a single sector. Such dependence often leads to economic vulnerabilities, including susceptibility to commodity price fluctuations and diminished competitiveness in other traditional sectors (Tserendorj and Purevjav, 2012; Taguchi and Ganzorig, 2018; Dagys *et al.*, 2020).

By the end of 2023, Mongolia's mining sector accounted for 29% of GDP, a 5% increase from 2020. In contrast, the contribution made by agriculture dropped to 10%, a 3% decrease, and that of manufacturing fell to 7%, reflecting a 2% decline. Additionally, mining products made up 86% of exports, while light manufacturing and agricultural products accounted for just 5% and 2%, respectively (NSO, 2024a, 2024b). These figures highlight Mongolia's growing dependence on mining and the weakening competitiveness of its traditional sectors.

To reduce dependence on raw material extraction and exports, diversifying Mongolia's economy and export structure is essential. Such diversification aims to mitigate risks and vulnerabilities associated with fluctuations in raw material prices. Therefore, strategic objectives, including supporting the manufacturing industry, establishing value-adding factories for agricultural and mineral products, and increasing the variety, quantity, and monetary value of export-oriented mining and non-mining products, are reflected in key policy documents in Mongolia. These include the Long-term Development Policy "Vision – 2050", the Medium-term "New Revival Policy", the Five-year Development Guidelines for Mongolia (2021-2025), and the Government Action Program (2024-2028) (Parliament of Mongolia, 2020, 2021a, 2021b, 2024).

Several studies have examined Mongolia's export diversification and proposed policy recommendations. Tsenguunjav and Munkhzul (2015) utilised the RCA index to identify export diversification strategies, assess products with export potential, conduct market research on non-mining products, and analyse production challenges, ultimately proposing strategies to enhance export diversification. Byambatsogt (2019) employed input-output analysis to evaluate the agricultural sector's role in economic diversification and calculate an economic expansion index. Khuslen and Davaajargal (2017) used the Economic Complexity Index and Product Space visualisations to identify priority sectors and products. Dagys *et al.* (2025) examined key sectors for diversification using an input-output methodology. Other studies, such as those of Batdelger (2022) and Helbe *et al.* (2020), provide descriptive analyses of export structures and sector development, identifying value chain challenges and suggesting export diversification strategies. These studies highlight the importance of developing non-mining products to diversify the economy and boost exports, alongside corresponding policy recommendations.

However, there is a notable research gap: no published study to date has systematically mapped the value chain of livestock-derived products, nor has anyone comprehensively identified the challenges encountered at each stage of the chain. This paper, therefore, aims to explore Mongolia's economic diversification potential in developing the processing industry for livestock-derived products through an RCA analysis and value chain mapping. Constraints at each stage are identified through a review of existing literature, and policy recommendations are proposed to address these challenges.

The remainder of the paper is organised as follows: Section 2 summarises diversification-related theories, methodology, and the data sources; Section 3 assesses the competitiveness and challenges of livestock-derived exports based on RCA and value chain mapping; Section 4 discusses policy recommendations; and Section 5 presents the conclusions.

Materials and methods

Theoretical framework

Economic diversification is crucial for any country, especially for those with economies heavily dependent on the extraction and export of natural resources. Researchers have studied economic diversification from various perspectives and established theoretical frameworks. The Revealed Comparative Advantage (RCA) concept measures a country's competitive strength in international trade based on its actual export performance (Balassa, 1965). Thus, focusing on competitive export products is essential for Mongolia's economic diversification. Conversely, Porter (1990) highlights that competitive advantage arises from a country's ability to innovate and upgrade its industries, which is also vital for diversification.

Furthermore, Porter's value chain concept can foster economic diversification by enhancing competitive advantage (Porter, 1985; Porter and Millar, 1985). This concept can be further extended to the Global Value Chain (GVC) framework, which emphasises input-output, territorial, and governance structures that are important for participation in global commodity chains (Gereffi, 1994).

Complementing Porter's competitive advantage concept, the Resource-Based View (RBV) approach highlights that a firm (or country)'s sustained competitive advantage depends on the potential of its resources, which possess four attributes: value, rareness, imitability, and sustainability (Barney, 1991).

Moreover, Economic Complexity Theory (ECT), introduced by Hidalgo and Hausmann (2009), provides a perspective on how a country's economy develops through the complexity of its productive structure, driven by the accumulation of capabilities, allowing the country to diversify more sophisticated and higher-value products.

Methodology and data employed

Based on the theoretical concepts discussed, it can be concluded that Balassa's RCA concept forms a foundational element for many of these theories. The core objectives of these theories are to achieve competitive advantage, diversify the economy through value addition, and leverage the uniqueness of resources and products. Therefore, we deemed it appropriate to identify products crucial for Mongolia's economic diversification that possess competitive export potential. Given that livestock products are the primary source for processing industries, we aimed to map the livestock value chain, pinpoint challenges at each stage, and explore potential solutions. We believe that addressing these value chain challenges would enable the production of higher-value, high-end, innovative, and knowledge-based products. This approach aligns with the unique characteristics of livestock resources by building capabilities for a complex productive structure and facilitates participation in GVCs. Ultimately, these efforts could pave the way for a more diversified economy in Mongolia.

To conduct this study, we calculate the RCA index for exported products to identify those crucial for economic diversification, the value chains they belong to, and their raw material sources. Next, we map the value chain for livestock-derived products, recognising that most non-mining products originate from the livestock sector. Challenges and constraints are identified at each stage of the chain based on a comprehensive review of existing literature. These findings provide the basis for formulating policy recommendations aimed at advancing economic diversification. Figure 1 shows the methodological framework used in this study.

The main indicator used to assess export products essential for economic diversification is the RCA index. The RCA index measures the competitiveness of country A for product i compared to the global average.

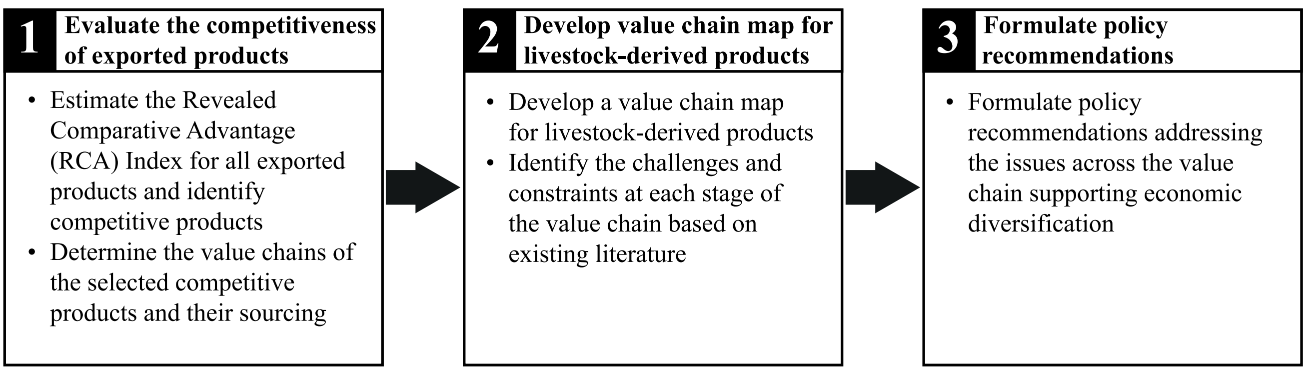

Figure 1: Logical framework scheme of the paper.
Source: Authors' elaboration

$$RCA_{Ai} = \frac{X_{Ai}/\sum_{j \in P} X_{Aj}}{X_{wi}/\sum_{j \in P} X_{wj}} \quad (1)$$

Where:

RCA_{Ai} – revealed comparative advantage index of country A for product i

P – product group, where $i \in P$

X_{Ai} – export value of product i for A

X_{wi} – world export value of product i

$\sum_{j \in P} X_{Aj}$ – total export value for country A across product group P

$\sum_{j \in P} X_{wj}$ – total world export value across product group P

The condition $RCA_{Ai} > 1$ indicates that country A has a comparative advantage in product i, suggesting the product is competitive relative to the world average.

A value chain map for products sourced from the livestock sector is developed as an adaption of the value chain framework developed by Porter and Millar (1985), as shown in Figure 2. The map illustrates the primary activities and identifies constraints at each stage of the chain in Mongolia.

The data used to calculate the RCA index were sourced from the International Trade Centre (ITC) database (ITC Trade Map, 2024). The following datasets for 2023 were utilised:

- Export value of products for Mongolia and the world, as HS4 digits.
- Total exports for Mongolia and the world, as HS4 digits.
- Factors negatively affecting the value chain for livestock-derived products were gathered from a comprehensive review of existing literature.

Results

Competitiveness of livestock-derived products

Figure 3 presents Mongolia's competitive export products, identified by an RCA index greater than one. The results indicate that Mongolia's competitive products predominantly consist of mining raw materials, livestock-derived raw materials, and manufactured goods produced from these resources. Detailed RCI scores are available in Appendix 1.

Among the mining products, coal, ferrous and non-ferrous metal ores, and precious metal concentrates emerge as the most competitive. Mongolia holds over 500 deposits of 80 different mineral commodities (Gerel *et al.*, 2021), including coal, iron ore, non-ferrous metals like copper, lead, zinc, tin, and tungsten, as well as precious metals such as gold and silver. The RCA index for these products ranges from over 2 to as high as 258, reflecting their presence in the global market. Notably, industrial minerals like feldspar, leucite, nepheline, and fluorspar exhibit strong competitiveness, with an exceptional RCA of 258, the highest among Mongolia's mining products. Additionally, RCA indexes of 61 and 63 for coal and copper, respectively, indicate significant competitiveness.

Livestock-derived raw materials and related manufacturing goods also demonstrate strong global competitiveness. Products related to the meat value chain, including primary products such as meat and by-products like guts, hides, and skins, show high RCA indexes. Additionally, wool, cashmere, and animal hair, along with semi-finished and finished goods such as garments made from these materials, further underscore Mongolia's comparative advantage in the global market. Notably, fine or coarse animal hair shows the highest RCA of 1570 among all exported products, while carded and combed wool and animal hair achieve an RCA of 67. These statistics highlight Mongolia's significant comparative advantage in wool and fibre products, attributed to the unique characteristics of the country's nomadic livestock sector. In particular, the highest RCA values for livestock-derived products, such as animal hair and meat, are closely linked to horse products, as horse-derived goods are relatively uncommon in other countries.

Several interrelated factors could influence the future competitiveness of the livestock sector and the RCA scores of livestock-derived products. Notably, there are numerous limitations on the production and export of high-potential products, particularly cashmere. China holds a near-monopoly in the global cashmere market, accounting for nearly 55% of global supply and dominating raw cashmere processing (Morton *et al.*, 2024). This dominance poses substantial challenges for Mongolia, as competition in the cashmere market remains fierce, and potential tariffs imposed by China

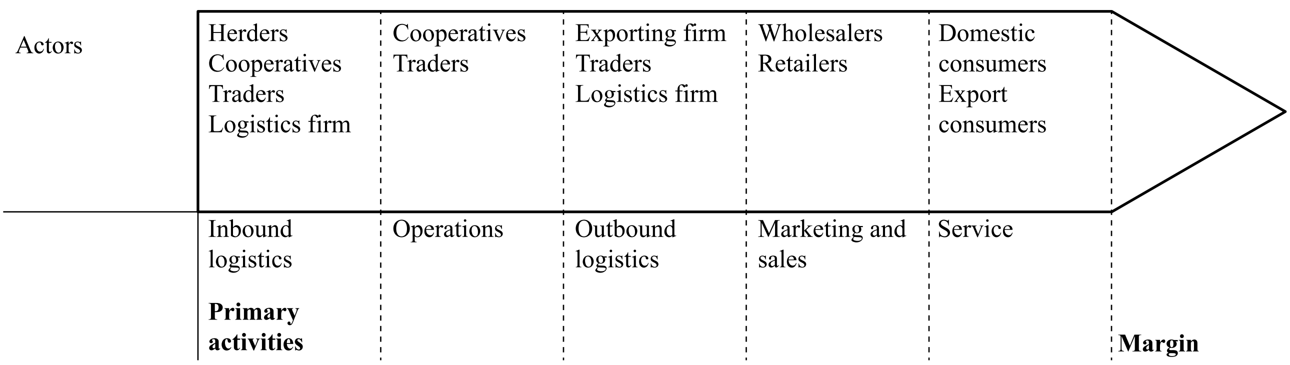

Figure 2: Value chain for livestock-derived products.

Source: Adapted based on Porter and Millar (1985)

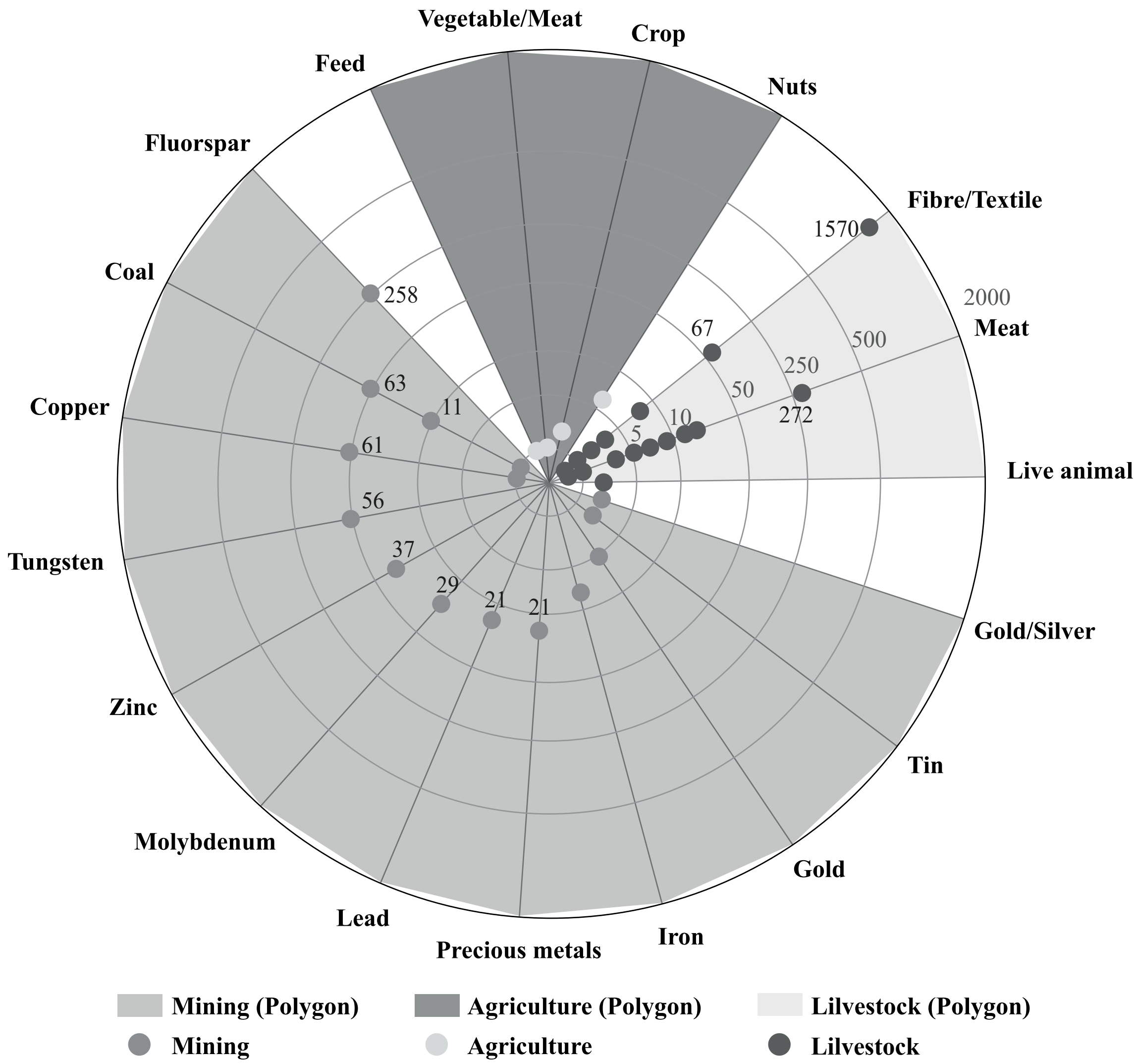

Figure 3: RCA index visualisation for Mongolia's competitive export products, average of 2019-2023 (HS4 digits).

Note: Detailed information regarding this figure can be found in Appendix 1.
Source: Authors' elaboration using Python (Python Software Foundation, 2024).

could further hinder Mongolian exports. Additionally, ongoing trade tensions between major global powers (Midfa, 2025) may further impact competition in the cashmere market and the overall competitiveness of Mongolia's cashmere products. Moreover, the growing demand for eco-friendly, ethically sourced, and sustainable products in European countries (EU, 2024), the primary high-end luxury cashmere market for Mongolian products, presents further difficulties for Mongolian producers and processors. Infectious livestock diseases also pose a persistent threat, potentially leading to international trade bans that restrict exports (Grieger, 2024).

The reliance on nomadic livestock makes the sector highly vulnerable to climate change, affecting both production resources and product quality. Intensifying environmental challenges, including dzuds, droughts, pasture degradation, and water shortages, exacerbate hardships for livestock producers. Furthermore, the deterioration of livestock quality and shifts in herding practices degrade product standards, impeding the development of high-end and sustainable processing industries (MULS, 2018).

Additionally, structural weaknesses in the livestock value chain, such as non-compliance with good practices and standards, limited infrastructure, particularly in road networks and storage facilities, and outdated technology in processing industries, could undermine competitiveness and further impact RCA scores (Dagys *et al.*, 2024).

Mongolia has 42 competitive export products across 19 value chains, with raw materials sourced from three primary sectors: mining, crop and vegetable production, and livestock. Out of these 19 value chains, 12 are linked to mining products, where nearly every mining product forms a distinct value chain due to differences in extraction and processing technologies, storage requirements, logistics, and sales.

In the crop and vegetable sector, four value chains are identified based on four products: two cereals, one nut, and one fodder product. In contrast, only three value chains are related to livestock products, with the meat value chain being the most significant, encompassing 11 export products.

Overall, 15 products are part of the 12 mining-related value chains, while 24 export-competitive products belong to 3 livestock-based value chains. This highlights the potential role of the livestock sector in reducing Mongolia's reliance on mining, supporting the non-mining manufacturing sector, and ultimately enhancing economic diversification. The next sections will focus on value chain mapping for livestock-derived products and the constraints encountered at each stage of the chain.

To assess the relative advantages of export products with higher RCA, a comparison of the selected 42 products across 19 value chains was conducted with the RCAs of similar products from Kazakhstan and Kyrgyzstan. These countries were chosen due to their similar economic structures and land-locked status. To facilitate comparison and reduce the high magnitudes of RCA values, natural logarithmic forms of the values were employed. This comparison, illustrated in Figure 4, reveals that the RCAs of most Mongolia's main export products are higher than those of Kazakhstan and Kyrgyzstan. This finding highlights Mongolia's greater potential for the production and exportation of livestock-derived and mining products and commodities.

A sensitivity analysis was performed to assess the robustness of the RCI results. Given that the export value of coal (2701) accounts for nearly half of the total exports, we examined how the RCI indices of the selected products changed when the coal export value increased and decreased by 10% and 20%, respectively. With a 10% change in coal export value, no product's RCI index fell below 1. However, a 20% increase in coal export value caused the RCI index for livestock by-products (0511) to drop below 1.

Additionally, because the RCI indices for certain products, such as livestock by-products (0510, 0511) and garments (6102), were below 1.5, we investigated their sensitivity to determine how their indices changed when their respective export values decreased by 10% and 20%, respectively. The RCI indices for 0510 and 6102 remained above 1.0 even when their export values decreased by 20%. However, in both cases of a 10% and 20% decrease in the export value of 0511, its RCI value fell below 1.

The results suggest that the RCI for all products remains robust to increases in coal export value up to 20%, except for 0511. Moreover, the decrease of up to 20% in export value for 0510 and 6102 also indicates the RCI for these products is robust. However, for 0511, its RCI falls below 1 due to a 20% increase in coal and a 10% decrease in its export value, indicating that this type of animal by-product should be processed and value-added domestically prior to exporting. Detailed information regarding the sensitivity analysis can be found in Appendix 2.

Value chain mapping for livestock-derived products

As a vital source of export-oriented products and a cornerstone for economic diversification, a value chain mapping of non-mining products sourced from the livestock sector has been conducted. Figure 5 illustrates the value chain of livestock-derived products.

Mongolia raises five types of livestock: camels, horses, cattle, sheep, and goats. As of 2023, the country had 67.6 million head of livestock (NSO, 2024b). The raw material supply for the light manufacturing industry is entirely dependent on this sector. Additionally, 20% of households directly rely on animal husbandry for their livelihoods, and herders comprise 25% of the national workforce (NSO, 2024b). These figures not only underscore the livestock sector's crucial role in the economy as a key driver of diversification but also

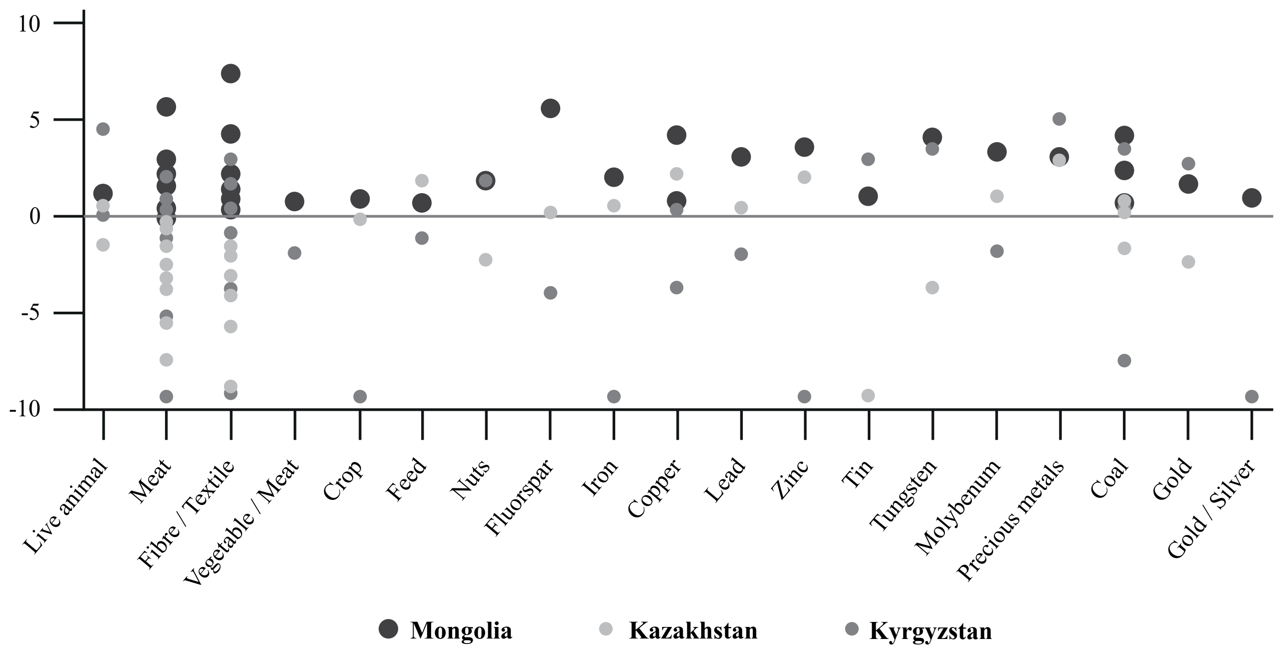

Figure 4: RCA index (logarithmic form) for selected products in different value chains in Mongolia, Kazakhstan, and Kyrgyzstan, average of 2019-2023 (HS4 digits).

Source: Authors' elaboration using Stata (StataCorp, 2013)

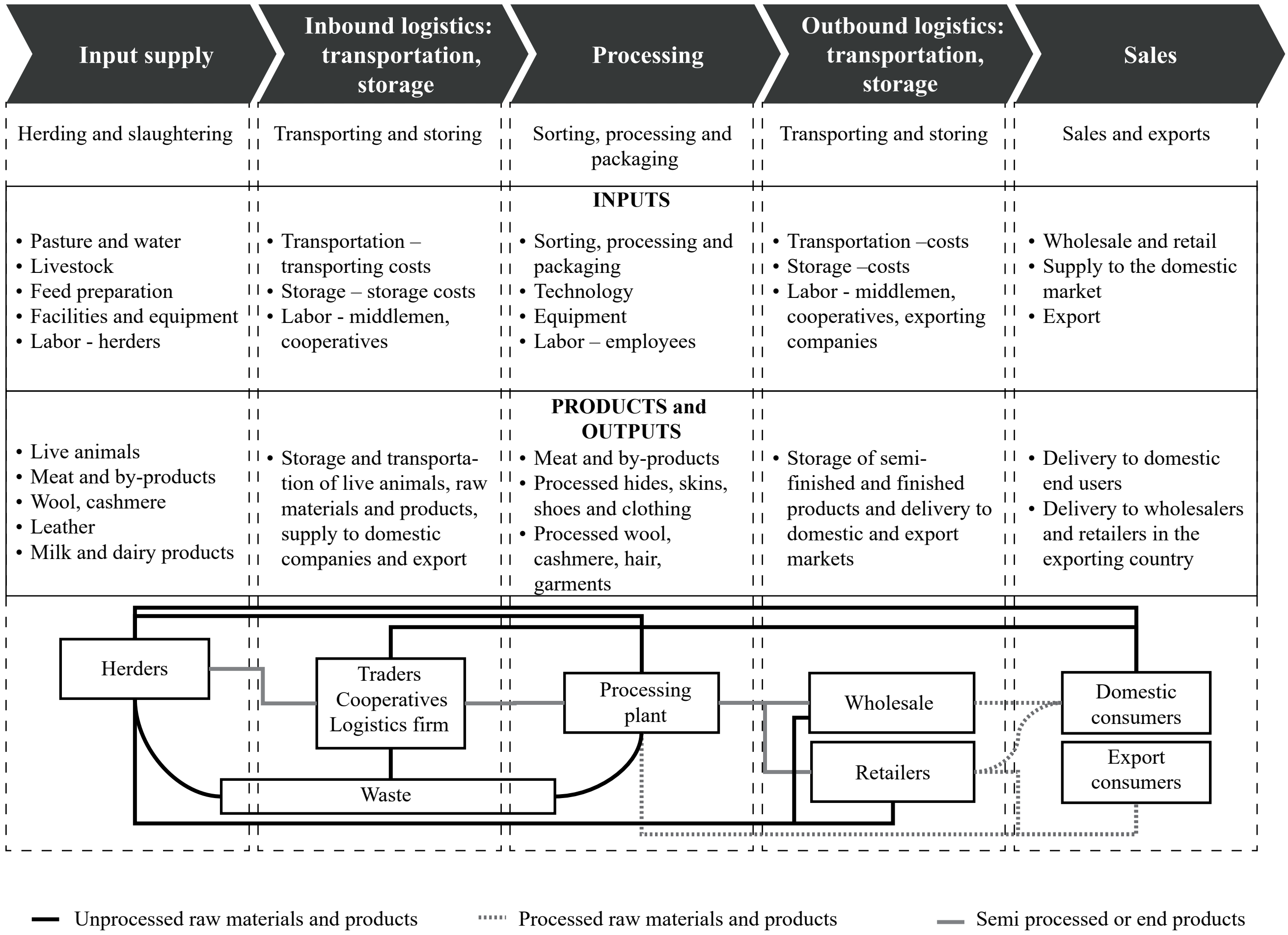

Figure 5: Value chain mapping of livestock products of Mongolia.
Source: Authors' elaboration based on Porter and Millar (1985)

highlight the sector's positive externalities in terms of livelihood for a significant portion of the population.

Livestock products such as meat, wool (from camels, sheep, and yaks), cashmere, hair, leather, milk, and by-products are supplied to the domestic market as final products or exported in raw, semi-processed, or processed forms. These products pass through various channels, including processing plants (manufacturing) and traders (intermediaries). Herders sell food products (meat, milk, and dairy) directly to wholesalers, retailers, processing plants, or end consumers, sometimes via traders. Conversely, non-food raw materials for the light industry, such as wool, cashmere, hides, and skins, are mainly passed through traders and cooperatives, and in some cases, supplied directly from producers to processing plants (Gonchigsumlaa *et al.*, 2018; MULS, 2018; Morton *et al.*, 2024).

Despite its importance, the level of processing for raw materials and products from animal husbandry remains relatively low. For example, only about 10% of the total meat production is processed in abattoirs that fully comply with standard requirements, while approximately 90% is processed using traditional methods, with significant volumes handled by small community-level slaughterhouses. Similarly, the processing of sheep and goat skins, wool, and hair is limited. However, advancements have been made in processing cashmere, yak wool, and hides (Tserensonom, 2017; Gonchigsumlaa *et al.*, 2018; JICA, 2024; Morton *et al.*, 2024).

While a comprehensive analysis of the value chain mapping constitutes a distinct research endeavour; this study focuses on identifying the challenges encountered within the value chain and exploring strategies for economic diversification.

Challenges Facing the Production of Livestock-derived Products

Challenges encountered at various stages of the livestock value chain significantly impact the processing and sale of export products. Figure 6 illustrates the constraints faced at each stage of the chain. Numerous negative factors affect the production, processing, logistics, trade, and export of livestock-derived products, with several key challenges identified below:

- **Non-compliance with standards:** The most significant challenge is the non-compliance with good practices and standards at every stage of production, storage, transportation, and processing (MULS, 2018; Enkhmaa, 2020; Agipar *et al.*, 2023; JICA, 2024).
- **Underdeveloped infrastructure:** Limited infrastructure poses risks to competitiveness in international

Input supply	Inbound logistics: transportation, storage	Processing	Outbound logistics: transportation, storage	Sales
• The low yield and productivity of pastoral animal products are significant concerns. • The sector's complete dependence on nature and climate makes it vulnerable to various risks. • Many animal products are priced very low, with some being nearly worthless due to a lack of buyers. • A high prevalence of highly infectious livestock diseases, particularly those that result in export bans, compounded by inadequate veterinary services. • Poor adherence to good animal husbandry and hygiene practices, as well as substandard animal husbandry protocols, negatively impacts the quality of both raw materials and final products.	• The costs of collecting, storing, and transporting raw materials are high because processing plants are concentrated in a central region. • Infrastructure is underdeveloped, with the domestic railway network primarily connecting China and Russia only through Ulaanbaatar, increasing road transportation costs. • A shortage of collection centres and warehouses for primary processing and proper storage of raw materials. • Adherence to good practices and standards for the storage and transportation of animal products is inadequate.	• The current practices do not adhere to good manufacturing and hygiene standards, nor do they meet food safety requirements and the regulations of importing countries. • Production technology and equipment are outdated, coupled with limited investment capacity among manufacturers. • The shift of employees to the higher-paying mining sector negatively affects the skilled labor pool available for light and food industries. • Significant waste is generated due to non-compliance with standards during both the production and transportation phases.	• There is a shortage of storage centres and warehouses specifically designed for the proper storage of semi-finished and finished, particularly food products in accordance with established standards and technology. • Compliance with good practices and standards for the storage and transportation of these products is insufficient. • Weak infrastructural development results in a heavy reliance on road transportation for finished products, which in turn increases costs.	• Numerous tariff and non-tariff restrictions and barriers imposed by importing countries pose significant challenges. • Being landlocked and situated between two large nations, China and Russia, Mongolia's exports to other countries heavily depend on these neighbours. • The high costs associated with export transportation, particularly for air-freighted goods, further inflate prices, reducing the competitiveness of these products. • Inadequate infrastructure development negatively impacts export capabilities.

Figure 6: Value chain mapping of livestock products of Mongolia.

Source: Authors' composition based on data from various sources, as indicated in the text

markets. For instance, road development is inadequate, and transportation primarily relies on vehicles (Helbe *et al.*, 2020; JICA, 2024; Morton *et al.*, 2024), leading to inefficiencies throughout the value chain from production to marketing. Additionally, there is a shortage of warehouses that meet standards and technical requirements for local storage of livestock products (Tserensonom, 2017; Gonchigsumlaa *et al.*, 2018; Agipar *et al.*, 2023; Ringler *et al.*, 2023; JICA, 2024). According to the Asian Development Bank (2018), logistics costs account for 30% of production expenses.

- **Waste management:** A major issue in production, logistics, and processing is the significant amount of waste generated (Tserensonom, 2017; Agipar *et al.*, 2023). Middlemen, who play a crucial role in the value chain (Tsenguunjav and Munkhzul, 2015; Erdenechuluun *et al.*, 2017; FAO, 2023), often exacerbate this issue by contributing to the underutilization of resources (MULS, 2018). For example, sheep wool and skins are sold at extremely low prices, approximately MNT 1,000 per kilogram (about USD 0.3). Due to the limited number of processing plants, these products are often discarded. Although the government introduced a subsidy of MNT 1,000 per kilogram of wool supplied to domestic factories, which helps reduce wool waste, sheep skins remain undervalued at MNT 500-1,000 (about USD 0.1-0.3), discouraging their sale. Middlemen often neglect these low-value raw materials, resulting in substantial waste. Meanwhile camel, horse, and cow hides are in relatively higher demand; however, poor adherence to slaughter standards leads to damage, creating additional waste at the processing stage (Tsenguunjav and Munkhzul, 2015; JICA, 2024).
- **Low productivity of pastoral livestock:** Whilst pastoral livestock farming is cost-effective, it suffers from low productivity and yields. Herders often prioritise increasing livestock numbers to boost income rather than improving livestock quality. This practice leads to negative consequences such as reduced productivity, lower yields, poor-quality raw materials, and significant waste during production and processing. (Agipar *et al.*, 2019; Agipar *et al.*, 2023; Dagys *et al.*, 2024)
- **Outdated technology:** Many processing plants operate with outdated equipment and inadequate technology, posing significant barriers to the export of non-mining products (Tsenguunjav and Munkhzul, 2015; Gonchigsumlaa *et al.*, 2018; MULS, 2018; Helbe *et al.*, 2020; Dagys *et al.*, 2023; JICA, 2024; Morton *et al.*, 2024).
- **Lack of skilled labour:** The manufacturing industry faces a shortage of skilled workers, undermining industrial competitiveness (Helbe *et al.*, 2020). This

issue is further exacerbated by the rapid growth of the mining sector and associated wage disparities, which lead to a shift of skilled labour from other sectors towards the mining sector (Gonchigsumlaa *et al.*, 2018; MULS, 2018; Dagys *et al.*, 2020; JICA, 2024).

- **Livestock diseases and trade bans:** The high prevalence of infectious livestock diseases, such as foot-and-mouth disease (FMD) and *peste des petits ruminants* (PPR), poses significant challenges. These diseases, coupled with international trade bans, restrict the export of livestock-derived products (Dagys *et al.*, 2017; Tserensonom, 2017; MULS, 2018; Agipar *et al.*, 2023; FAO, 2023).
- **Trade barriers:** Tariff and non-tariff barriers imposed by importing countries create significant obstacles to exports (Gonchigsumlaa *et al.*, 2018; Tsetsegmaa, 2020). While Mongolia has made strides in establishing trade facilitation agreements with partner countries, further efforts are required for continued progress (Dagys *et al.*, 2017; Tsetsegmaa, 2020, 2022; JICA, 2024).
- **Policy and investment gaps:** The lack of a robust legal framework, inconsistent government policies, and insufficient financial investment further hinder the manufacturing sector's development (EDP, 2020).
- **Climate change:** The reliance on nomadic livestock, which is entirely dependent on environmental and climatic conditions, renders the sector highly susceptible to the risks posed by climate change, contributing to livestock losses due to dzuds and droughts, pasture degradation, and water shortages (Oniki and Dagys, 2017; Agipar *et al.*, 2019; Gros *et al.*, 2022; Dagys *et al.*, 2023). These risks affect production resources, as well as the quantity, yield, and quality of livestock-derived products, ultimately affecting the sale and export of these goods (MULS, 2018; Agipar *et al.*, 2023; Ringler *et al.*, 2023; Agipar *et al.*, 2024; JICA, 2024; Morton *et al.*, 2024).

Policy recommendations

Based on the findings from the value chain mapping of livestock-derived products, the following policy recommendations at each stage of the value chain are proposed:

At the production stage

- Improve animal health status through public-private partnerships:
  - To export livestock-derived products and penetrate high-end global markets, improving animal health and securing verification of disease-free status are essential. Establishing disease-free zones or compartments with traceability systems, where feasible, is a critical step toward achieving this objective.
  - For effective implementation of these strategic objectives, the veterinary system, including both public services and private veterinary units, must be sufficiently robust to control infectious diseases that lead to trade bans. Therefore, government investment and support are imperative to strengthen capacity-building programmes, enhance the competitiveness of veterinary units, and improve their overall capacity.
  - Shifting herders' attitudes towards prioritising livestock health is also crucial. Emphasising the importance of fostering collaboration through public-private partnerships, including herders, private veterinary units, and public authorities, will support these efforts.
- *Improve the quality of animal breeds by changing herders' attitudes:* To improve productivity and yield, herders' attitudes should be changed through specific policies and awareness campaigns. Economic incentives, such as tax benefits, soft loans, and government support for herders and herder cooperatives, can encourage the adoption and compliance of production-level standards and good practices.

At the logistics stage

- *Enhance community-level raw material collection and supply chain systems:* Developing a robust raw material collection and supply chain system is crucial, with particular emphasis on addressing issues related to raw material preparation, storage, and transportation. At present, informal middlemen predominantly dominate the raw material preparation system, whilst inadequate infrastructure exacerbates these challenges. Establishing a unified raw material supply system at the community level for producers or herders is essential for implementing standards and practices, as well as ensuring proper primary processing, storage, and transportation.

At the processing stage

- *Enhance the competitiveness of processing plants through targeted financial and investment support:* Given the weak financial capacity of processing plants and their outdated technology and equipment, it is crucial to provide financial and investment support to these facilities. Upgrading technology and equipment is vital to enhancing their competitiveness. Investment can be attracted through public-private partnerships, redirecting a portion of mining revenue into this sector, offering soft loans, subsidies, and long-term concessions, and fostering collaborations with key importing partner countries.
- *Enhance the processing level of raw materials through public-private partnerships:* Enhancing the processing level of raw materials and products derived from traditional livestock in Mongolia is crucial for reducing the country's economic dependence on a single sector and promoting diversification. To achieve this strategy, public, private, and foreign direct investments can be mobilised to develop advanced technologies and techniques for processing plants.

At the export and sales stage

- *Establish a one-stop service supporting trade, export, marketing, traceability and blockchain technologies:* The establishment of a one-stop service for trade, export, and marketing support for manufacturers of export-oriented products should align with the digital transition and advancements in information technology, including blockchain technology for traceability of livestock-derived products.
- *Ease export barriers through trade facilitation agreements and free trade zones:* Efforts should focus on reducing tariff and non-tariff barriers imposed by trade partners. This can be achieved through trade facilitation agreements, the establishment of joint free trade zones between countries, or the creation of joint-processing enterprises with key trading partners and importing countries.
- *Facilitate the diversification of export markets by conducting comprehensive studies on markets and non-tariff barriers, and propose potential solutions:* At present, Mongolia's livestock-derived export products are limited to a few markets, such as sheep meat exported to the Middle East (e.g., Iran and Iraq), and horse meat, unprocessed, and primary-processed hides, skins, wool, and hair exported to China. To diversify and expand market opportunities, it is essential to explore potential new markets, including major countries like the United States and economic blocs such as the European Union (EU), the Association of Southeast Asian Nations (ASEAN), and the Eurasian Economic Union (EAEU). For each semi-processed and processed livestock-derived product, a detailed study should examine non-tariff barriers and import requirements. Based on these findings, strategies must be developed to overcome barriers and ensure compliance with market-specific requirements.

At the policy coordination and implementation stage

- *Develop and implement a holistic and comprehensive livestock sector policy and strategy:* This will enable the unified implementation and adequate coordination of policies related to pasture protection, animal breeding, veterinary services, animal husbandry risks, herders' livelihoods, and the collection, storage, and trade of raw materials.
- *Develop a comprehensive long-term strategic plan for the advancement of Mongolia's livestock-derived product processing industry:* This approach facilitates inter-sectoral coordination, addresses value chain challenges at multiple levels, and optimises the value addition process, thereby strengthening the capacity to compete in the global market with high-quality, competitively priced non-mining products.
- *Develop and implement an export development strategic plan:* Currently, Mongolia lacks a comprehensive export development strategic plan. This plan should incorporate potential processing and export-oriented products identified through RCA analysis, detailed value chain assessments, export market destinations, import requirements, and trade barriers of key trading partners. Additionally, it should address potential gaps and provide corresponding solutions, including an outline of necessary policy measures and supporting documents, financial and investment proposals, and other actionable steps to facilitate export growth.

At all stages of the value chain

- *Ensure compliance with good practices and standards across the value chain:* Introducing, implementing, and adopting relevant standards and good practices across all stages of the value chain is essential. This includes Good Animal Husbandry Practices (GAHP) at the production level; Good Distribution Practices (GDP) during collection, transportation, and storage; and Good Manufacturing Practices (GMP), Good Hygiene Practices (GHP), ISO 9001:2015 Quality Management Systems (QMSs), and ISO 22000:2018 Food Safety Management Systems (FSMSs) at the processing level. Furthermore, ensuring compliance with the import requirements of trade partners, such as Halal certification throughout all stages of the meat value chain, is critical for exporting meat products to Middle Eastern and Central Asian countries. Non-compliance with these standards, practices, rules, and instructions can lead to numerous negative consequences, including significant waste generation, compromised quality of final products, increased costs, diminished competitiveness, failure to meet the requirements of importing partners, and exposure to non-tariff restrictions.

Conclusions

The research aimed to identify strategies for diversifying Mongolia's economy by analysing the RCA index methodology and mapping the value chain for livestock-derived products. The RCA index analysis identified globally competitive products among Mongolia's exports. These products were categorized into sectors and value chains, with an emphasis on determining which value chains are crucial for diversifying the economy and advancing the industrial sector. The RCA analysis revealed 42 export-competitive products within the HS4 category, encompassing mining raw materials, livestock raw materials, and processed products that can hold their ground in the global market. These products are categorised into 19 distinct value chains: 12 linked to mining, three to livestock, and four to agricultural production sources. Notably, 15 out of 42 products depend on mining resources, while 24 are based on animal husbandry raw materials, highlighting the significance of livestock-derived raw materials and value-added products in Mongolia's economic diversification. In particular, the identification of 11 products within the meat value chain that exhibit a comparative export advantage underscores the necessity for targeted strategies and investments to bolster this value chain.

Given the competitiveness of livestock-derived products and their potential role in economic diversification, a detailed mapping of the value chain for livestock-derived products was created. This mapping integrated challenges encountered at each stage of the value chain, as identified through existing literature. Key challenges include a lack of adherence to good practices and standards throughout the value-addition process, leading to significant raw material and product waste. In primary production, issues such as animal health, low productivity, and vulnerability to natural and climatic risks threaten production stability. Weak infrastructure further exacerbates inefficiencies in the collection, storage, and transportation of raw materials during the logistics stage. At the processing stage, outdated technologies and techniques increase operational costs and reduce competitiveness, compounded by a shortage of skilled labour. Finally, as a landlocked nation situated between two large countries, Mongolia faces logistical challenges at the export stage, including tariff and non-tariff barriers imposed by importing countries that significantly impede trade.

This study focuses on identifying opportunities for economic diversification based on the current state of production and exports. It does not assess the economic impact of diversification, the development of the manufacturing sector, or the effectiveness of government policies in promoting diversification. Importantly, it is necessary to acknowledge the limitations of the RCA methodology, particularly within Mongolia's price-sensitive and export-dependent economy. The RCA index, whilst useful for identifying comparative advantages, does not account for factors such as market volatility, demand fluctuations, or the sustainability of resource use. Furthermore, the value chain mapping, relying on existing literature, provides an overview rather than a detailed analysis, and may not fully capture the dynamic and evolving nature of the sector. Future research should explore these limitations by incorporating quantitative data on price elasticity, market demand, and environmental impact.

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Appendix

Appendix 1: RCA index for competitive products exported by Mongolia, on average of 2019-2023 (HS4 digits).

HS code	Group	Product label	Value chain	RCI
'0104	Animal & Animal Products	Live sheep and goats	Live animal	3
'0106		Live animals (excl. horses, bovine animals, swine, sheep, goats, poultry)	Live animal	3
'0204		Meat of sheep or goats, fresh, chilled or frozen	Meat	4
'0205		Meat of horses, asses, mules or hinnies, fresh, chilled or frozen	Meat	272
'0504		Guts, bladders and stomachs of animals (other than fish)	Meat	5
'0507		Ivory, tortoiseshell, whalebone and whalebone hair, horns, antlers, hooves, nails, claws	Meat	17
'0510		Ambergris, castoreum, civet and musk; cantharides; bile	Meat	1
'0511		Animal products, unfit for human consumption	Meat	1
'0802	Vegetable Products	Other nuts, fresh or dried	Nuts	6
'1205		Rape or colza seeds, whether or not broken	Crop	3
'1506		Other animal fats and oils and their fractions	Vegetable/Meat	2
'1602	Foodstuffs	Prepared or preserved meat, meat offal, blood or insects	Meat	7
'2302		Bran, sharps and other residues	Feed	2
'2529	Mineral Products	Feldspar; leucite, nepheline and nepheline syenite; fluorspar	Fluorspar	258
'2601		Iron ores and concentrates, incl. roasted iron pyrites	Iron	8
'2603		Copper ores and concentrates	Copper	61
'2607		Lead ores and concentrates	Lead	21
'2608		Zinc ores and concentrates	Zinc	37
'2609		Tin ores and concentrates	Tin	3
'2611		Tungsten ores and concentrates	Tungsten	56
'2613		Molybdenum ores and concentrates	Molybdenum	29
'2616		Precious-metal ores and concentrates	Precious metals	21
'2701		Coal; briquettes, ovoids and similar solid fuels manufactured from coal	Coal	63
'2702		Lignite, whether or not agglomerated	Coal	11
'2704		Coke and semi-coke of coal, of lignite or of peat	Coal	2
'4104	Raw Hides, Skins, Leather, & Furs	Tanned or crust hides and skins of bovine, horse	Meat	2
'4105		Tanned or crust skins of sheep or lambs	Meat	9
'4106		Tanned or crust hides and skins of goats	Meat	22
'5101	Textiles	Wool, neither carded nor combed	Fibre/Textile	8
'5102		Fine or coarse animal hair, neither carded nor combed	Fibre/Textile	1 570
'5103		Waste of wool or of fine or coarse animal hair, incl. yarn waste	Fibre/Textile	4
'5105		Wool and fine or coarse animal hair, carded or combed	Fibre/Textile	67
'5108		Carded or combed yarn of fine animal hair	Fibre/Textile	2
'5109		Yarn of wool or fine animal hair, put up for retail sale	Fibre/Textile	2
'5111		Woven fabrics of carded wool or of carded fine animal hair	Fibre/Textile	2
'5507		Artificial staple fibres, carded, combed or otherwise processed for spinning	Fibre/Textile	2
'6102		Women's or girls' overcoats, car coats, capes, cloaks, anoraks	Fibre/Textile	1
'6106		Women's or girls' blouses, shirts and shirt-blouses, knitted or crocheted	Fibre/Textile	4
'6117		Made-up clothing accessories, knitted or crocheted	Fibre/Textile	3
'7108	Stone / Glass	Gold, incl. gold plated with platinum	Gold	5
'7111		Base metals, silver or gold, clad with platinum	Gold / Silver	3
'7403	Metals	Copper, refined, and copper alloys	Copper	2

Source: Authors' calculations based on ITC Trade Map (2024).

Appendix 2: Sensitivity analysis of RCA index, on average of 2019-2023 (HS4 digits).

HS code	Base RCI	RCI estimated based on the changes in export value of selected products									
		Coal				**'0510**		**'0511**		**'6102**	
		10% increase	**10% decrease**	**20% increase**	**20% decrease**	**10% decrease**	**20% decrease**	**10% decrease**	**20% decrease**	**10% decrease**	**20% decrease**
'0104	3.4	3	4	3	4	3	3	3	3	3	3
'0106	3.4	3	4	3	4	3	3	3	3	3	3
'0204	4.3	4	5	4	5	4	4	4	4	4	4
'0205	272.4	261	288	261	288	275	275	272	275	275	275
'0504	5.1	5	5	5	5	5	5	5	5	5	5
'0507	17.3	17	18	17	18	17	17	17	17	17	17
'0510	**1.35**	1	1	1	1	**1.23**	**1.09**	1	1	1	1
'0511	**1.02**	1	1	**0.98**	1	1	1	**0.92**	**0.82**	1	1
'0802	6.0	6	6	6	6	6	6	6	6	6	6
'1205	2.5	2	3	2	3	3	3	3	3	3	3
'1506	2.1	2	2	2	2	2	2	2	2	2	2
'1602	6.8	7	7	7	7	7	7	7	7	7	7
'2302	2.0	2	2	2	2	2	2	2	2	2	2
'2529	258.0	247	273	247	273	260	260	258	260	260	260
'2601	7.6	7	8	7	8	8	8	8	8	8	8
'2603	61.3	59	65	59	65	62	62	61	62	62	62
'2607	21.3	20	23	20	23	22	22	21	22	22	22
'2608	36.7	35	39	35	39	37	37	37	37	37	37
'2609	2.9	3	3	3	3	3	3	3	3	3	3
'2611	56.3	54	60	54	60	57	57	56	57	57	57
'2613	28.6	27	30	27	30	29	29	29	29	29	29
'2616	20.7	20	22	20	22	21	21	21	21	21	21
'2701	62.8	**66**	**60**	**66**	**60**	63	63	63	63	63	63
'2702	11.1	11	12	11	12	11	11	11	11	11	11
'2704	2.0	2	2	2	2	2	2	2	2	2	2
'4104	1.5	1	2	1	2	2	2	2	2	2	2
'4105	9.4	9	10	9	10	9	9	9	9	9	9
'4106	21.7	21	23	21	23	22	22	22	22	22	22
'5101	8.4	8	9	8	9	8	8	8	8	8	8
'5102	1570.1	1,503	1,659	1,503	1,659	1,585	1,585	1,570	1,585	1,585	1,585
'5103	3.5	3	4	3	4	4	4	4	4	4	4
'5105	67.3	64	71	64	71	68	68	67	68	68	68
'5108	2.4	2	3	2	3	2	2	2	2	2	2
'5109	1.6	2	2	2	2	2	2	2	2	2	2
'5111	1.6	2	2	2	2	2	2	2	2	2	2
'5507	1.5	1	2	1	2	2	2	2	2	2	2
'6102	**1.36**	1	1	1	1	1	1	1	1	**1.24**	**1.10**
'6106	3.9	4	4	4	4	4	4	4	4	4	4
'6117	2.6	2	3	2	3	3	3	3	3	3	3
'7108	5.0	5	5	5	5	5	5	5	5	5	5
'7111	2.6	2	3	2	3	3	3	3	3	3	3
'7403	2.1	2	2	2	2	2	2	2	2	2	2

Note: light grey highlights with bold text indicate cases where the RCA index falls below 1 due to changes in export value. Dark grey highlights with bold text indicate the RCA values that remain robust despite changes in their respective export value.
0510: Ambergris, castoreum, civet and musk; cantharides; bile; 0511: Animal products, unfit for human consumption; 6102: Women's or girls' overcoats, car coats, capes, cloaks, anoraks.
Source: Authors' calculations based on ITC Trade Map (2024).

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The Effects of Investment Support on Performance of Farms: The Case of Application of the Rural Development Programme in Slovakia

The paper estimates the firm level impact of the Common Agricultural Policy (CAP) investment subsidies on gross value added, profits, employment, and productivity of farms in Slovakia, and evaluates the effectiveness of support provided through the Rural Development Programme. We employ a Propensity Score Matching Difference-in-Differences econometric approach on a database of commercial farms for the period 2006-2015. The results of this paper show that the farm investment support stimulated growth of gross value added, farm profits, and employment in the agricultural sector, while it reduced labour productivity. Investment support helped to maintain rural jobs, which occurred partly at the expense of labour productivity. The paper stresses high deadweight costs of investment support within the CAP, which should be considered when planning and implementing new CAP interventions.

Keywords: CAP, investment support, PSM estimator, Slovakia

JEL classifications: Q18, Q12, C21, O13, H25.

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Introduction

One of the objectives of the Common Agricultural Policy (CAP) of the European Union (EU) is to support the competitiveness of farms and their restructuring. In the programming period 2007–2013, 11 billion EUR of the EU budget was devoted to the support of competitiveness through investment into agricultural production and food processing. Investment support to farms and processing companies from Rural Development Programmes (RDP) of the EU continued in the programming period 2014–2020 and similar support has been allocated in the current period of 2023–2027. Similarly, the recovery plan for Europe also aims to allocate a substantial amount in the sector to address the adverse economic and social effects caused by the coronavirus pandemic.

Investment support is coupled to agricultural production, whereas the majority of farm subsidies within the EU’s CAP are decoupled from production. Decoupled subsidies include mainly direct payments that are allocated per hectare of agricultural land. Investment support is project-based. Farmers submit investment projects for financing within specific calls for projects. Less than 15 percent of direct payments are still linked to agricultural production and are distributed based on cultivation of a specific commodity or rearing specific farm animals – they are coupled subsidies.

Investment support stimulates farm investment and the adoption of productivity-enhancing modern technology (FAO, 2011). The European Commission explicitly mentions in its proposal for the post-2013 CAP the challenge of food security and the EU’s goal to support long-term food supply potential and meet the growing world food demand (European Commission, 2012; Rizov *et al.*, 2012).

Investment support remains an important objective of the CAP in the current programming period 2023–2027 (European Commission, 2023). Supporting agricultural productivity is one of the nine’s main objectives and one of the three’s economic objectives of the CAP, the other two being supporting incomes of farmers and strengthening the position of farmers in the supply chains. In the case of Slovakia, the Slovak strategic plan for the CAP 2023 – 2027 stresses the importance of increasing productivity of Slovak farms and the whole value chain and SWOT analysis accompanying the Strategic plan considers improvement of productivity one of the most important objectives of the Strategic Plan of the Common Agricultural Policy in Slovakia.

It is therefore important and relevant for taxpayers, policymakers, and analysts to evaluate the effects and efficiency of such support not only in Slovakia, which is a primary objective of our analysis, but also in other EU countries. The main goal of this paper is to evaluate the impact of investment support to farms provided within Rural Development Programme in the programming period 2007-2013 in Slovakia. Specifically, we analyse the impact of investment support on gross value added of farms, labour employment, labour productivity, and profit. Our null hypothesis is that investment support increases productivity of farms, gross value added, profits, and employment.

There is growing literature attempting to estimate the performance of the RDP support in general (e.g., Arata and

Sckokai, 2016; Bakucs *et al.*, 2019; Kuhfuss and Subervie, 2018; Mack *et al.*, 2018; Pufahl and Weiss, 2009; Udagawa *et al.*, 2014) and investment support (e.g., Bartova and Hurnakova, 2016; Desjeux *et al.*, 2014; Kirchweger *et al.*, 2015; Kirchweger and Kantelhardt, 2015; Medonos *et al.*, 2012; Michalek *et al.*, 2016; Olper et al., 2014; Petrick and Zier, 2011). Specifically, for Slovakia, Michalek (2009) evaluated the impact of investment support to farms in early years of Slovakia's membership in the EU (2004–2006). The results are likely to have been strongly affected by the period of the analysis, which was characterised by a rapid adjustment of the economy and agricultural sector to EU policies and institutions due to the EU accession. This article evaluates the RDP programming period of 2007–2013 when the Slovak economy and the agricultural sector in particular had already adjusted to EU membership. Slovakia fully participated in EU policies, including the RDP, for the whole programming period.

The results for Slovakia are especially relevant because (a) agricultural production in Slovakia is dominated by large farms and therefore differs from the structure of farms observed in other countries where family farms prevail[1], and (b) Slovak farms, like farms in all countries of Central and Eastern Europe, are technologically less advanced than those in the Western countries of the EU and investment support helps them to close the technological gap (Pokrivcak *et al.*, 2019).

Our results therefore provide evidence on the effect of investment subsidies on market-oriented large farms, which normally do not have problems obtaining credit from banks. This contrasts with the effect of investment subsidies on small family farms that suffer from credit constraint. Furthermore, our results shed some light on EU investment support to farms in Central and Eastern Europe where institutions, including financial institutions as well as regulatory capacity of the state, are lagging behind those in the more advanced countries of the EU. Moreover, the advantage on focusing specifically on a country case study instead of covering several countries or all EU is that the implementation details of each RDP measure – including the investment support (e.g., eligibility criteria, size of the support) – usually varies between member states. Given such variations in RDP implementation, a more desirable approach is to perform estimations for each regional unit (Michalek *et al.*, 2020).

Literature review

Government is significantly involved in EU agriculture. Annually, the EU spends around 50 billion EUR on support for rural areas, environmental public goods, agricultural incomes and production subsidies. According to the European Commission (the EU's executive branch) agricultural policies are crucial to support the incomes of farmers and to sustain rural communities by creating jobs and preventing outward-migration from rural areas (European Commission, 2012). In the new Common Agricultural Policy post-2020, the European Commission further stresses the important role of agricultural subsidies in fostering jobs in rural areas, improving incomes and productivity of farms and attracting new people in agricultural sector (European Commission, 2023).

The main rationale for agricultural policies is to correct market failure by supporting provision of public goods and coping with economic externalities of agricultural production. Furthermore, agricultural policies are used to eliminate imperfections in rural financial and insurance markets so as to enhance agricultural productivity (Blancard *et al.*, 2006; Ciaian and Swinnen, 2009; Hennessy, 1998; Roche and McQuinn, 2004). There is overwhelming evidence that rural credit markets are imperfect and lead to significant credit constraint of farms. Agricultural subsidies help to relax credit constraint either by directly providing investment funds for farms or indirectly by increasing farms' profitability and collateral (Ciaian *et al.*, 2010). Imperfect insurance markets hinder investment in riskier activities that have high return if there are no insurance policies available for farmers (Hennessy, 1998; Roche and McQuinn, 2004).

Improving the competitiveness of the agricultural sector is one of the key priorities of the CAP. One of the main CAP instruments used to promote the agricultural competitiveness is through the farm investment support granted under the Rural Development Programme (European Commission, 2012; European Union, 2013). Several studies attempted to investigate whether the CAP, the farm investment support in particular, contributes towards this objective.

Agricultural subsidies have important impacts on agricultural markets. Besides affecting farmers' income, studies have shown that agricultural subsidies distort input and output markets and thus alter the rents of other agents active in the agricultural sector (for example consumers or input suppliers). The impact of agricultural subsidies on distribution of income depends heavily on the type of subsidies, structure of markets and the existence of market imperfections (Alston and James, 2002; de Gorter and Meilke, 1989; Gardner, 1983; Guyomard *et al.*, 2004; Salhofer, 1996; Ciaian and Swinnen, 2009). Studies also evaluate, among other aspects, the impacts of subsidies on the environment and agricultural public goods (e.g. van Beers and van den Bergh, 2001; Khanna *et al.*, 2002) or productivity and market distortions (e.g. Chau and de Gorter, 2005; Goodwin and Mishra, 2006; Sckokai and Moro, 2006).

In general, investment support is expected to stimulate on-firm investments on supported firms which can be translated into an improvement in their performance, particularly when farms have constrained access to credit. If farms are not credit constrained then the support is expected to lead to deadweight effects as farms are expected to carry out investments that they would do even in the absence of the support (Brandsma *et al.*, 2013; Michalek *et al.*, 2016, 2020). Further, the impact of the investment support might be reflected by reducing the capital cost that is expected to induce the substitution of capital for labour, and thus supported firms might become more capital intensive (Daly *et al.*, 1993; Michalek *et al.*, 2020).

According to Rizov *et al.* (2013), there are two opposed views on the agricultural subsidies in the context of the Common Agricultural Policy of the European Union. The Euro-

[1] Large farms also dominate in the Czech Republic and play important roles in Bulgaria and Baltic countries.

pean Commission stresses the role of agricultural subsidies in fostering jobs in rural areas, improving incomes and productivity of farms and attracting new people in agricultural sector (European Commission, 2023). Agricultural policies are crucial to support incomes of farmers and to sustain rural communities by creating jobs and preventing out-migration from rural areas (European Commission, 2012).

On the other hand, agricultural subsidies have been criticised for distorting agricultural markets and labour allocation in the economy by constraining or preventing structural change that is essential for economic growth and development (Johnson, 1973; Gardner, 1992; OECD, 2008). With respect to agricultural employment, some studies do indeed find a positive impact of subsidies on agricultural employment (Breustedt and Glauben, 2007; Olper *et al.*, 2014), but others find no or mixed impacts (Barkley and Flinchbaugh, 1990; Petrick and Zier, 2011) and yet others find a negative impact (Berlinschi *et al.*, 2014).

Regarding the farm investment support, the literature finds mixed results. Several studies found mostly positive effects of investment subsidies on various farm indicators such as gross added value, farm profitability, productivity, and income level (e.g., Kirchweger and Kantelhardt, 2015; Salvioni and Sciulli, 2011; Medonos *et al.*, 2012; Spicka and Krause, 2013). Other studies, however, found zero or negative impact of the RDP investment support, for example, on labour employment or efficiency and productivity (e.g., Salvioni and Sciulli, 2011; Gabe and Kraybill, 2002; Beason and Weinstein, 1996; Lee, 1996; Bagella and Becchetti, 1998; Harris and Robinson, 2004; Bernini and Pellegrini, 2011; Olper *et al*., 2014, Musliu, 2020).

The extent of government involvement in the agricultural production is difficult to explain through recourse to the market failure argument, though. Economic theory states that agricultural policies significantly distort incentives and reduce productivity (Johnson, 1973; OECD, 2008) by changing relative prices of outputs and inputs, increasing, or decreasing income of farmers, increasing, or reducing risks of agricultural production, and changing farm structure (size of farms, exit or entry of farms) (OECD, 2024). Many agricultural policies involve a combination of effects. For example, investment grants applied in the EU increase the income of farmers, reduce risk, and affect exit and entry of farms.

There are different types of subsidies and their effects, therefore, also differ. For example, subsidies to less favoured areas generally subsidise farms that cultivate less productive land and therefore these types of subsidies keep inefficient farms in production which reduces efficiency (Latruffe and Desjeux, 2016). Similarly, agri-environmental subsidies compensate farmers for imposition of additional environmental constraint on use of inputs. However, one study suggests that the empirical evidence is not clear-cut (Lakner, 2009), while others find no or a positive effect (Mary, 2013; Dudu and Kristkova, 2017). Investments in human and physical capital may be productivity enhancing and cost-reducing, as improved knowledge of efficient farming practices can lead to better use of technology and land (Boulanger and Philippidis, 2015; Dudu and Kristkova, 2017). There is related literature analysing the impact of different types of CAP subsidies (e.g., direct payments, RDP) on productivity of farms. Depending on the type of subsidy and institutional factors (e.g., the presence of farm credit constraint), theoretical papers suggest that agricultural subsidies may have either positive or negative impact on farm productivity (e.g., Rizov *et al*., 2012; Hennessy, 1998; Ciaian and Swinnen, 2009). For example, Latruffe *et al.* (2009) find a negative impact of CAP subsidies that are linked to production on managerial efficiency of French farms.

Agricultural subsidies might reduce productivity by introducing technical and allocative inefficiency. This occurs when farmers invest in supported activities that might be less productive and over-invest in subsidised inputs. Agricultural subsidies also reduce incentives to minimise costs and create soft budget constraint that leads to inefficiency and lower productivity growth (Alston and James, 2002; Rizov *et al.*, 2013; Leibenstein, 1966; Minviel and Latruffe, 2017; Kornai, 1998).

Cechura (2012) asserts that the most important factors which determine both technical efficiency and TFP are the factors connected with institutional and economic changes, in particular a dramatic increase in the imports of meat and increasing subsidies. Lakner (2009) shows that the agri-environmental and investment subsidies have negative effects on the technical efficiency of organic dairy farms in Germany, while Zhu and Oude Lansink (2010) discover a negative impact of subsidies linked to production on technical efficiency of crop farms in Germany, the Netherlands and Sweden. By analogy, Zhu *et al.* (2012) find that production subsidies and input subsidies negatively impact technical efficiency of dairy farms in Germany and the Netherlands. In the specific case of Slovakia, Michalek (2009) estimated that the effect of the SAPARD programme, granted to farmers before the EU accession, had a negligible or negative impact on farm profits and gross value added, while the estimated effect on the agricultural employment was slightly positive.

On the other hand, productivity is increased when agricultural policies solve rural credit or insurance imperfections, provide public goods and cope with negative externalities (Blancard et al., 2006; Ciaian and Swinnen, 2009, Hennessy, 1998; Roche and McQuinn, 2004). The estimates of Bartova and Hurnakova (2016) show a positive net effect of the RDP 2007-2013 investment support on farm performance in Slovakia.

Overall, with respect to agricultural employment, the literature states both positive and negative effects of subsidies. Positive effects result from higher incomes which keep farmers in agriculture rather than moving to other sectors of the economy. Negative effects of agricultural subsidies on employment result traditionally from substitution of labour by capital. Subsidies also relax credit constraint which leads to structural change towards less farms of bigger sizes. Higher income due to subsidies, however, indirectly leads to reduction of employment because farmers use enhanced income to invest in skills and education which allows them to find jobs outside of agriculture (Goetz and Debertin, 1996, 2001; Barkley and Flinchbaugh, 1990; Ciaian *et al.*, 2010; Berlinschi *et al.*, 2014). Indirect negative effects on employment might outweigh positive effects and therefore the net effect is a matter of empirical estimation (Garrone *et* *al.*, 2019). Garrone *et al.* (2019) estimated econometrically using detailed EU-wide panel data for 2015 regions of the EU collected within Clearance Audit Trail System that CAP subsidies are costly in the European Union. One saved job in the agricultural sector costs taxpayers 324 000 EUR annually, which is 27 000 EUR monthly.

Farm investment support in Slovakia

In this paper we cover the Measure 121 – modernisation of farms – (referred to as investment support) granted under the Rural Development Programme 2007–2013. The objective of this measure was to increase competitiveness of agricultural farms through better utilisation of the factors of production and the application of new technologies and innovations. The support was targeted towards the reduction of production costs, improvement of labour conditions, increasing the number of farms with modern buildings, new technologies and equipment saving energy, as well as towards introducing or expanding the use of information and communication technology (RDP Slovakia 2007–2013).

Investment support was implemented by 7 calls for proposals realised between 2008 and 2015. Project evaluation criteria of individual calls gave preference to projects that:

- led to expansion of modern and competitive crop production including production of fruits and vegetables with higher value added;
- contributed to modernisation of animal production;
- led to expansion of direct sale of production to consumers;
- directed investment to specific locations (less developed regions);
- targeted investment to specific segments and types of farms;
- invested in certain sizes of projects.

Overall, 2,173 projects were supported through this measure by the end of 2015 with a total amount of 490.9 million EUR. Regarding the number of farms, 1,498 farms were supported, of which 445 were natural persons. Around 55% of all supported projects were realised in animal production, while 26.65% were in crop production. In animal production, projects supported mainly cattle, while in crop production, cereals sector was supported. Regarding type of supported investments, 271 million EUR (55%) of grants was used on financing capital investment, while 219.4 million EUR (45%) was used on financing investment into buildings.

Materials and methods

Econometric Approach

We analyse the impact of investment support to farms (treatment) on their performance as measured by the average treatment on the treated (ATT) a widely applied method in the literature for counterfactual impact analysis of policies (e.g., Hoken and Su, 2015; Michalek *et al.*, 2016; Michalek *et al.*, 2018). We estimate the average difference in outcome variables (e.g., farm productivity, employment, value added or profits), Y, of farms that had received support (D=1) and those that had not received investment support (D=0). The causal effect of investment support is the difference between the potential outcome of farms with investment support (treated farms), Y_1, and the potential outcome of farms without investment support (untreated farms), Y_0: $Y_1 - Y_0$. The expected value of potential outcome of farms without investment support is not directly observed. To use non-supported farms as a control group would result in a selection bias, because the selection in or out of the investment support scheme is not random, implying that means of Y_0 for farms with investment support (D=1) and Y_0 for those without investment support (D=0) may differ systematically, even in the absence of the support programme (Heckman and Robb, 1985; Heckman, 1997; Smith, 2000; Smith and Todd, 2005). In the RDP farms self-select to apply for the investment grant which makes the selection bias particularly relevant. To deal with the selection bias, we define the average treatment on the treated (ATT) conditional on the probability distribution of observed covariates:

$$\mathrm{ATT}(Z) = E(Y_1 - Y_0 | X = Z, P(Z) = p, D = 1) \qquad (1)$$

where X is a set of variables representing the pre-exposure attributes (covariates) of farms, Z is a subset of X representing a set of observable covariates, P is a probability distribution of observed covariance Z. However, the estimation of ATT is difficult due to high dimensionality of the conditioning problem.

According to Rosenbaum and Rubin (1983), the dimensionality of the conditioning problem can be significantly reduced by implementing matching methods using balancing scores b(Z) such as propensity score. For random variables Y and Z and for discrete variable D, the propensity score is defined as the conditional probability of receiving the treatment (i.e., receiving investment support) given pre-treatment characteristics, $Z: p(Z) = \Pr(D = 1|Z) = E(D|Z)$. Rosenbaum and Rubin (1983) show that if treatment is random conditional on Z, it is also random conditional on $p(Z)$:

$$E[D|Y, \Pr(D = 1|Z)] = E[E(D|Y, Z|Y, \Pr(D = 1|Y)] \qquad (2)$$

so that $E(D|Y,Z) = E(D|Z) = Pr(D = 1|Z)$, which implies that $E[D|Y, \Pr(D = 1)|Z)] = E[D|Pr(D = 1|Z)]$, where $Pr(D = 1|Z)$ is a propensity score. This implies that, when outcomes are *independent of receiving treatment* conditional on Z, they are also *independent of treatment* conditional on the propensity score, $Pr(D = 1|Z)$. Hence, the conditional independence remains valid, if we use the propensity score $p(Z)$ instead of covariates Z or X.

Estimating a conditional participation probability by employing a parametric method, such as *probit* or *logit*, or *semi-parametrically* reduces dimensionality of the matching problem substantially to one dimension only, i.e., univariate propensity score. An important feature of this method is that after individuals have been matched, the unmatched comparison individuals can be easily separated out and are not directly used in the estimation of treatment effects.

The Propensity Score Matching (PSM) estimator for the ATT can be written as:

$$\tau^{\mathrm{PSM}} = E[p(Z)|D = 1][E(Y_1|D = 1, p(Z)] - - [E(Y_0|D = 0, p(Z)] \quad (3)$$

which corresponds to the mean difference in outcomes over the common support, appropriately weighted by the propensity score distribution of PO members (Caliendo and Kopeinig, 2008).

Difference-in-Differences PSM estimator

While the PSM can be applied to control for selection bias on observables at the beginning of the programme, a combination of the PSM with Difference-in-Differences (DID) methods (conditional DID estimator) allows for controlling of selection bias in both observables and unobservables (e.g., Heckman *et al.*, 1997; Bratberg *et al.*, 2002; Smith and Todd, 2005). The PSM-DID measures the impact of receiving investment support by using differences between comparable treated farms (*D*=1) and control group (non-treated) (*D*=0) in the period before, *t*', and after, *t*, the investment support implementation:

$$\text{PSM-DID} = \{\textstyle\sum_i[Y_{\mathrm{it}}|(D = 1) - Y_{\mathrm{it}}|(D = 0)] - - \textstyle\sum_i[Y_{\mathrm{it'}}|(D = 1) - Y_{\mathrm{it'}}|(D = 0)]\}/n \quad (4)$$

where $Y_{\mathrm{it}}|(D = 1) - Y_{\mathrm{it}}|(D = 0)$ is the difference in mean outcomes between *i* with investment support and *i matched* non-investment support farm *after* the access to investment support, and $Y_{\mathrm{it'}}|(D = 1) - Y_{\mathrm{it'}}|(D = 0)$ is the difference in the mean outcome between *i* with investment support and *i matched* with no investment support in *prior* period to the programme implementation.

The PSM-DID estimator thus eliminates differences in the initial conditions (observable heterogeneity) and differences between both groups (receivers and non-receivers) of farms. The first difference in the PSM-DID estimator, which is the change over time within farms, eliminates the influence of time-invariant unobserved individual heterogeneity. The second difference, between receivers of investment support and control group, eliminates general changes common to all farms (receivers and non-receivers) (Michalek *et al.*, 2018).

Data

In this paper we use the individual economic, financial and accountancy data of farms obtained from Informačné listy (Information Letters) of the Ministry of Agriculture and Rural Development of the Slovak Republic. The database contains detailed accountancy data for commercial farms. This data was merged with the database of the Agricultural Paying Agency of the Slovak Republic which contains data on projects supported from Rural Development Programme 2007–2013.

We use data for 2006 and 2015. The choice of the data for 2006 and 2015 is determined by the timing of the application of the investment support as part of the RDP. This paper analyses the impact of the RDP support granted during the financial period 2007-2013 which was extended to 2014 due to the delayed adoption of the new CAP reform for the period 2014-2020. The data we employ in this paper covers one year before the start of the investment support (2006) and one year after the end of the support (2015). This allows us to evaluate the impact of investment support during the period 2007-2014. Further, the farm database allows us to identify farms with and without investment support granted in the period 2007-2014.

We consider four outcome variables, *Y*: farm gross value added (GVA), farm profits, farm employment and labour productivity (GVA per annual work unit, AWU). The purpose of including these variables is to capture both the revenue side and the input side of the farm performance.

Results and discussion

Table 1A (in appendix) provides data on how PSM balances the farms with investment support from RDP and those from the control group. Balancing reduced the difference between the treated farms and non-treated farms in observable covariates. Further, after matching the differences are no longer statistically significant, suggesting that matching reduced the bias associated with observable covariates. These results suggest that matching reduced the differences between treated farms and non-treated farms between 80% and 99% for the relevant covariates that are statistically significant before matching.

The tests of joint significance of covariates show that the likelihood ratio test was statistically significant before matching and insignificant after matching. The pseudo-R2 was reduced after matching by a factor greater than 3 relative to its value before matching. The matching reduced the overall bias by more than 94%. These tests show that the differences in the covariate means were eliminated between the treated farms and the control group (Table 2A).

Figure 1 plots the density-distribution of propensity scores for supported farms (treated farms) and the control non-treated group. Overall, the visual examination of Figure 1 suggests that the distributions of the propensity scores for treated and the control groups are more similar (and therefore highly comparable) after matching.

The estimated impacts of the investment support on gross value added and profit are reported in Table 1. The results show that the farm investment support had a positive but rather low effect on GVA per farm between 2007 and 2015. Due to investment support, the GVA increased on average by 31 025 EUR. While GVA of supported farms increased on average by 14 038 EUR, the GVA of non-supported firms decreased by 16 987 EUR. Using this estimated effects alongside considering 1,498 of farms that received the investment support, the investment support granted within the Rural Development Programme of Slovakia led to the aggregate increase of GVA by 46.5 mil EUR. The efficiency of the investment support − measured by the ratio of the average effect of investment support on farm GVA (31 025 EUR) and the average support per farm (302 877 EUR) − was 9.76 EUR or investment support needed for increase of GVA by 1 EUR.

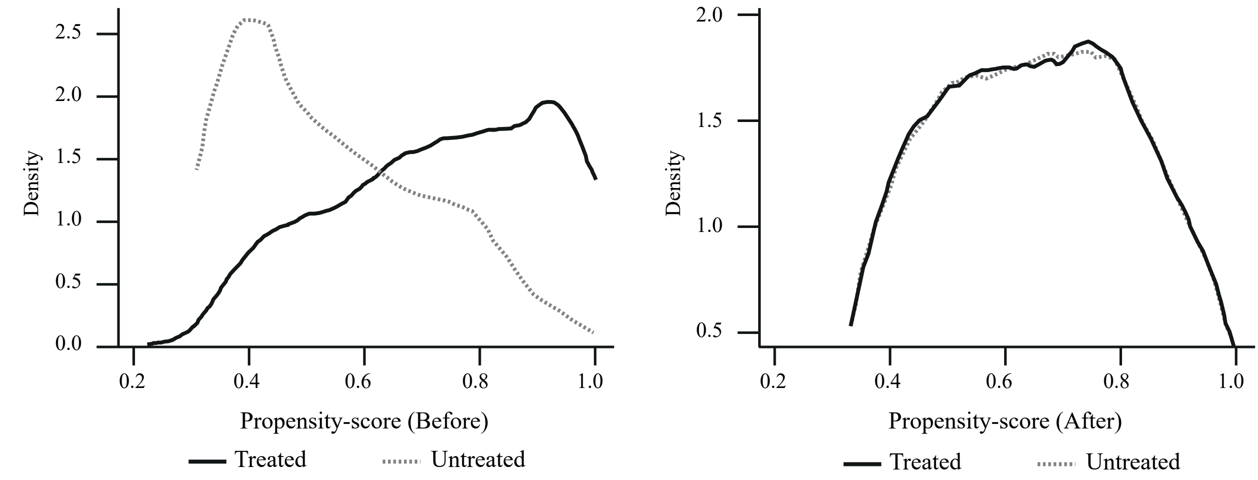


Figure 1: Distribution of propensity scores for supported farms (treated farms) and the control non-treated group before and after PSM balancing.

Source: own composition

Table 1: Effects of Investment Support on Gross Value Added and Profit.

	Estimated Effects of farm investment support		
	GVA per farm	**Profit per farm before taxation**	**Profit per farm from operations**
Effect of the investment support per farm	+31 025€	+20 908€	+17 893€
% change			
Treated	+15.3%	+210%	+50.5%
Non-treated	-10.2%	-464%	-85%
Change			
Treated	+14 038€	-7 458€	-10 941€
Non-treated	-16 987€	-28 367€	-28 834€
Efficiency of investment support	9.76 € of support for growth of GVA by 1€	14.49 € of support for growth of profit before taxation by 1€	25.61 € of support for growth of profit from operations by 1€

Source: own composition

Further, the results in Table 1 show that between 2007 and 2015 the profits of both supported and non-supported farms declined. Supported farms experienced a lower decline in profits than non-supported farms[2]. Thus, the investment support caused an increase of profit by 20 908 EUR per farm and profit from operations by 17 893 EUR. In terms of the efficiency indicator, one EURO of the investment support increased farm profit before taxation and profit from operations by 14.5 EUR and 25.6 EUR, respectively. These results are also presented in Figure 2.

Between 2007 and 2015 employment declined at both supported and non-supported farms. Decline of employment at supported farms was lower (12.3 AWU) than at non-supported farms (15 AWU). Thus, in aggregate the farm investment support increased (preserved) employment by 4,164 jobs (AWU), which was 2.74 jobs per supported farm. When considering the total investment support allocated, this implies the average cost per one preserved job is 108 891 EUR (Table 2 and Figure 3).

[2] Profit includes profit from operations and profit from financial operations. Profit before taxation is therefore profit from operations plus profit from financial operations.

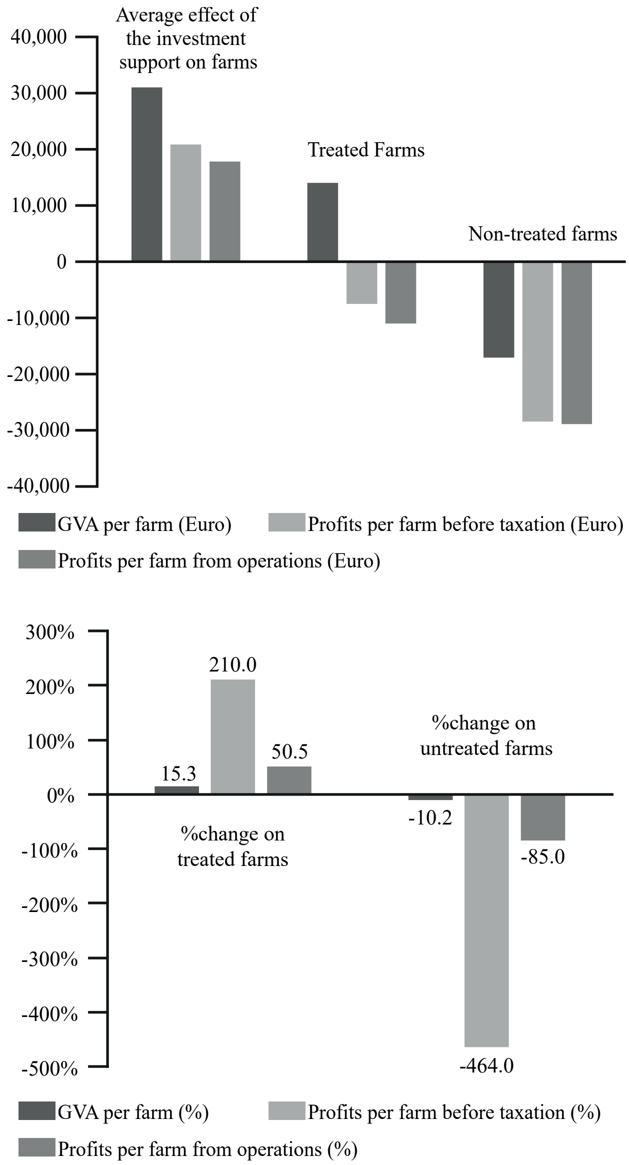


Figure 2: The estimated impact of investment support on Gross Value Added, profits per farm before taxation and Profits per farm from operations in Euros and in % change

Source: own composition

Table 2: Effects of investment support on employment.

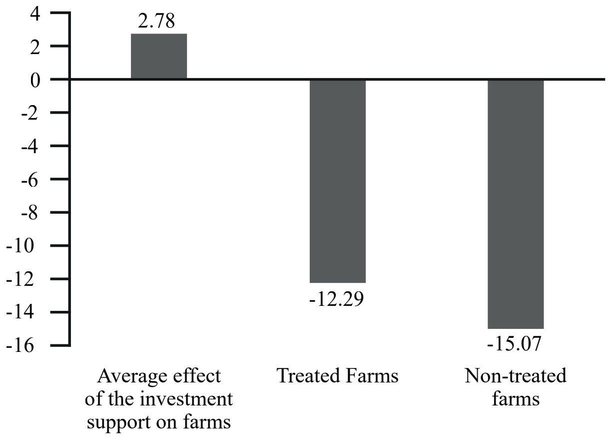
	Estimated effects of the farm investment support on employment per farm
Effects on employment at farms	2.78 AWU
% change of employment	
Treated	+7.60 %
Non-treated	-44.8%
Change of employment	
Treated	-12.29 AWU
Non-treated	-15.07 AWU
Efficiency of investment support	108 891 EUR per job created

Source: own composition

Table 3: Effects of investment support on labour productivity.

	Estimated Effects of farm investment support Labour productivity
Effects on labour productivity, GVA/AWU	-1 138 EUR/AWU
% change of productivity (% GVA/AWU per farm)	-44%
% change of labour productivity	
Treated	+ 44.0%
Non-treated	+ 58.9%
Change of labour productivity	
Treated	+3 763 EUR/AWU
Non-treated	+4 902 EUR/AWU

Source: own composition



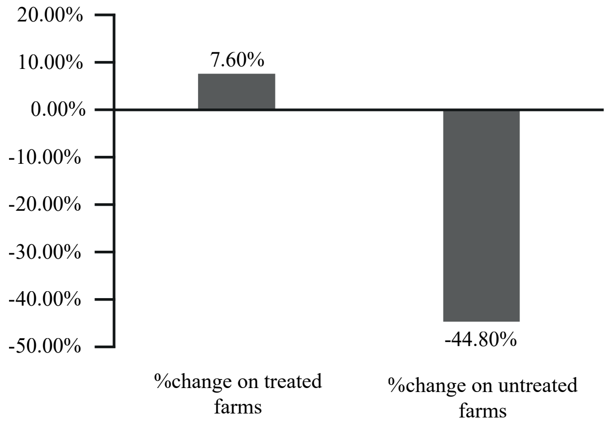
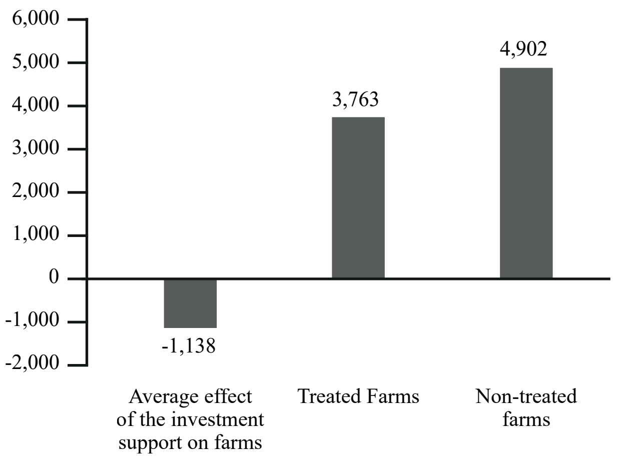


Figure 3: The estimated impact of investment support on Employment in AWU and in % change

Source: own composition



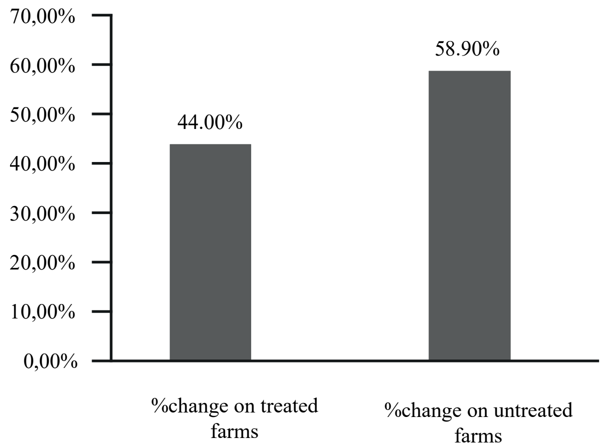


Figure 4: The estimated impact of investment support on labour productivity in GVA/AWU and in % change.

Source: own composition

The positive impact of the programme on employment was reduced because of the significant transfers of support to current consumption of farms through significant growth of expenditures on wages and salaries for supported firms while there was no similar increase of expenditures on wages and salaries of non-supported.

The estimated results suggest that farm investment support had a negative effect on labour productivity. Between 2007 and 2015 labour productivity of both supported and non-supported farms increased but increase of productivity among non-supported farms was higher (Table 3). The main objective of the investment support was to maintain employment and one of the conditions for receiving support was that farms must create new jobs. Furthermore, investment into labour intensive commodities was predominantly supported (fruits, vegetables, animal production) rather than into capital or land intensive commodities such as cereals or oilseeds. Consequently, supported farms reduced employment less than non-supported farms (Figure 4).

Overall, the estimated results show that the investment support had high level of deadweight cost, at 87%. That is, a large proportion of supported firms would undertake projects in approximately similar size even without the investment support. Many firms, which did not receive the investment support realized projects from own or borrowed funds. The high deadweight cost confirms high administrative intensity of project preparation, filing of projects and their implementation and monitoring, while the gains are rather small as shown above.

Low agricultural value added and employment per hectare are major challenges of the Slovak agricultural policy (Ministry of Finance of Slovakia, 2019, Ministry of Agriculture and Rural Development of Slovakia, 2023, Ciaian et al., 2009). The reason is that the Slovak farming sector is dominated by large corporate farms that specialize in production of cereals and oilseeds that have high productivity of labour, but low value added and employment per hectare. The investment support reflected on these challenges and included selection criteria that prioritized investment projects into expansion of modern fruits and vegetables production and animal production that are characterized by higher value added and employment than dominant oilseeds and cereals production. Similarly, to increase GVA and employment, farms with direct sales to consumers were also prioritised. Farms were therefore motivated to adjust production structure towards more labour-intensive types of agricultural commodities and activities.

The investment support in Slovakia also included the criterion of creating additional employment on farms, which supported farms had to fulfil. Non-supported farms, on the other hand, were free not to expand artificially farm employment and their labour productivity increased relative to supported farms.

There is a need for political discussion at the EU level, whether value added, and specifically rural employment should be a priority in the Common Agricultural Policy, or the priority should instead be on competitiveness and productivity of farms, which is in accordance with the EU food security objective.

Many large farms in the EU do not face financial constraints that would significantly prohibit them from investing using their own or commercially borrowed financial resources. In Slovakia, for example, a financial gap exists mainly among small farms and farms of young farmers (Pokrivcak and Toth, 2022). Many farms that were main beneficiaries of the investment support in Slovakia therefore did not face financial constraints that would prevent them from investing without the investment support. A large proportion of supported firms would undertake projects of approximately similar size even without the investment support. This fact is reflected in the large deadweight costs of the investment support, meaning that significant amount of resources has been used to support farms that do not really need the support.

Discussion on the use of public funds for supporting large farms in the European Union have been around for a long time. Most scientific papers and policy documents recommend targeted subsidies to farms that need them (Pokrivčák et al., 2020). The high deadweight costs of investment grants is one of the reasons for targeted subsidies. Our paper stresses that policy makers that decide on the implementation of farm subsidies should consider whether large farms face budget constraints or make a significant contribution to the provision of public goods. The current CAP contains several policy instruments that can be used to reduce the deadweight costs of public support like degressivity or capping of support for large farms – both direct payments and investment grants.

However, as stressed by political economy of farm subsidies literature in the EU (Swinnen, 2018; Pokrivcak et al., 2006), there is a political economy aspect of agricultural policy making and EU decision making that prevents politicians from significantly reducing support to large farms.

Conclusions

The objective of the paper has been to estimate the impact of the farm investment support granted in Slovakia under the EU Rural Development Programmes during the programming period 2007–2013. We have applied a Difference-in-Differences propensity score matching (PSM) methodology to estimate the farm level impact of the support using farm level data of large commercial farms for 2006 and 2015. We have estimated the impact of the support on gross value added of farms, labour employment, labour productivity, and profits.

The results of this paper show that the farm investment support caused both improvement and a decrease in competitiveness for supported firms in Slovakia because it stimulated growth of gross value added, farm profits, and maintenance of employment in the agricultural sector, while at the same time it reduced labour productivity. Overall, the estimated results show that the aggregate effect of the investment support on gross value added of farms reached 46.5 million EUR. This represents around 10% of the total investment support granted to farmers. Investment support, however, had a negative effect on productivity of farms. Productivity of labour declined due to investment support by 1138 EUR of GVA per AWU. The decline of labour productivity represents approximately 5% of the productivity of labour in Slovak agriculture.

These estimates suggest that the effect of investment support on rural economy in Slovakia is therefore ambiguous. On the one hand, it leads to the enhancement of farms' gross value added, while on the other side, it leads to the decline of labour productivity. Further, the investment support has had a positive effect on the growth of employment. The support helped farms to maintain 4,164 rural jobs. This is about 6% of the total employment in the Slovak agriculture in the period 2006-2015.

The data shows that in the period between 2004 and 2015 employment in the Slovak agriculture declined from 96,000 employees to about 70,000 employees (Slovak Statistical Office, various years). This decline of employment in the Slovak agriculture was likely caused by technological progress, which led to increase in productivity of labour, and by the reduction of competitiveness of the Slovak agriculture at the European level, which is manifested by worsening of trade balance in agricultural and food products. Our estimates show that although the RDP support did not cause the creation of new jobs, it helped to maintain jobs which alleviated the negative trends of agricultural employment observed in Slovakia. That is, the supported firms reduced employment less than unsupported firms, causing a lower aggregate agricultural employment decline in Slovakia that would have occurred without the support. However, the efficiency of the investment support in maintaining employment was relatively low. One preserved job through investment support cost 109,000 EUR of public money.

Investment support helped to maintain rural jobs, which occurred partly at the expense of labour productivity. Projects creating rural jobs were prioritised in the selection process. Production of fruits and vegetables and animal production are sectors of agricultural economy that are the most labour intensive and create the most value added per hectare (Ciaian, et al., 2004). To create rural jobs, the project selection criteria prioritised farms that:

- expanded modern and competitive crop production, especially fruits and vegetables with higher value added;
- contributed to modernisation of animal production;
- expanded the direct sale of production to consumers;
- directed investment to specific locations (less developed regions);
- targeted investment to specific segments and types of farms; and
- invested in certain sizes of projects.

The programme also gave preference to projects in animal production and production of fruits and vegetables which are labour intensive activities. On the other hand, firms that had not received support, invested own or borrowed funds into projects that created less jobs but enhanced labour productivity.

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Appendix

Table A1: Balancing treated and non-treated farms by PSM.

Variable	Unmatched / Matched	Mean Treated	Mean Control	% bias	% bias reduction	t-test t	t-test p>|t|
Total assets	Unmatched	81,887	33,856	67.9		7.35	0
	Matched	53,679	53,372	0.4	99.4	0.06	0.952
Fixed Assets	Unmatched	48,062	18,931	65.6		7.11	0
	Matched	30,821	29,176	3.7	94.4	0.52	0.605
Value of land	Unmatched	1,944.4	876.06	17.8		1.84	0.066
	Matched	1,186.8	1,399.2	-3.5	80.1	-0.6	0.551
Value of Buildings	Unmatched	26,301	10,679	59.6		6.59	0
	Matched	17,691	16,984	2.7	95.5	0.33	0.744
Value of grassland	Unmatched	1,341.9	549.32	17.3		1.97	0.05
	Matched	769.35	558.14	4.6	73.4	0.66	0.511
Value of Animals	Unmatched	2,868.4	951.53	66.8		7.11	0
	Matched	1,763.3	1,681.6	2.8	95.7	0.39	0.7
Financial capital	Unmatched	1,895.5	503.61	32.9		3.41	0.001
	Matched	817.18	629.49	4.4	86.5	0.91	0.363
Variable capital	Unmatched	33,054	14,486	60		6.45	0
	Matched	22,131	23,319	-3.8	93.6	-0.55	0.582
Total sales	Unmatched	3,103.6	1,292.3	16.8		1.77	0.077
	Matched	2,026.2	1,801.5	2.1	87.6	0.31	0.758
Sales of own production	Unmatched	38,476	17,262	54.9		6.06	0
	Matched	27,759	25,491	5.9	89.3	0.76	0.445
Sales of crop production	Unmatched	15,743	8,385.8	45.2		4.88	0
	Matched	12,534	13,072	-3.3	92.7	-0.41	0.685
Sales from agrotoursm	Unmatched	143.97	0.73786	13		1.32	0.189
	Matched	2.0367	2.6266	-0.1	99.6	-0.31	0.757
Total costs	Unmatched	60,344	26,791	63.2		6.87	0
	Matched	43,050	42,272	1.5	97.7	0.19	0.847
Material and energy costs	Unmatched	24,640	10,720	53		5.91	0
	Matched	18,258	16,833	5.4	89.8	0.68	0.497
Labour costs	Unmatched	12,263	5,498.6	66.5		7.16	0
	Matched	8,723.6	8,286.6	4.3	93.5	0.56	0.573
Bank loans	Unmatched	8,462.7	3,118.5	44.9		4.76	0
	Matched	4,683.8	5,257.9	-4.8	89.3	-0.81	0.421
Labour	Unmatched	49.248	23.245	65.3		7.09	0
	Matched	36.429	33.637	7	89.3	0.9	0.37
Total subsidies	Unmatched	11,090	5,203.3	76.1		8.33	0
	Matched	7,951.2	7,855.1	1.2	98.4	0.16	0.874
Total land	Unmatched	1,544.8	823.83	68.9		7.71	0
	Matched	1,204.3	1,236.2	-3.1	95.6	0.35	0.727
Total LPIS Land	Unmatched	1,424.9	749.81	72.2		8	0
	Matched	1,107.9	1,138.5	-3.3	95.5	-0.39	0.699
Arable land	Unmatched	1,036.8	527.6	61.8		6.74	0
	Matched	822.71	822.47	0	100	0	0.997
Grassland	Unmatched	351.42	198.45	33.9		3.84	0
	Matched	260.66	263.44	-0.6	98.2	-0.07	0.947
RDP support	Unmatched	63,403	21,195	33.1		3.46	0.001
	Matched	36,331	31,538	3.8	88.6	0.72	0.471

Variable	Unmatched / Matched	Mean Treated	Mean Control	% bias	% bias reduction	t-test t	t-test p>|t|
LFA area	Unmatched	734.71	352.25	46.8		5.18	0
	Matched	562.87	574.05	-1.4	97.1	0.15	0.884
Wheat production	Unmatched	1,122.3	543.7	49.9		5.35	0
	Matched	877.28	857.66	1.7	96.6	0.21	0.831
Maize production	Unmatched	635.98	345.83	28		2.99	0.003
	Matched	483.78	491.65	-0.8	97.3	0.1	0.918
Oilseed production	Unmatched	421.46	223.93	43.8		4.82	0
	Matched	365.61	353.46	2.7	93.8	0.3	0.767
Sugar beet production	Unmatched	1,135.7	622.34	20.8		2.31	0.021
	Matched	1,021.6	1,054.7	-1.3	93.6	0.13	0.895
Potato production	Unmatched	40.934	12.219	13.7		1.4	0.161
	Matched	11.954	10.572	0.7	95.2	0.25	0.805
Milk production per cow	Unmatched	3,462.5	1,567.2	68		7.79	0
	Matched	2,606.3	2,586	0.7	98.9	0.08	0.938
Income before taxes	Unmatched	1,843.3	940.29	19		2.09	0.037
	Matched	1,068.4	1,022.2	1	94.9	0.11	0.911
Income before taxes per labour	Unmatched	48,768	90,274	-7.5		-0.82	0.412
	Matched	55,505	30,296	4.6	39.3	0.64	0.525
Income before taxes without subsidies	Unmatched	-9,359	4,385.7	-61.4		-6.77	0
	Matched	-7,198.4	-7,133.6	-0.8	98.7	0.09	0.927

Source: own calculations

Table A2: Matching quality indicators before and after propensity score matching.

	Pseudo R2	LR chi2	p>chi2	MeanBias	MedBias
Unmatched	0.173	138.97	0.000	45.9	49.9
Matched	0.047	31.73	0.530	2.7	2.7

Source: own calculations

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Farm Characteristics and Resources: The C5.0 Classification Tree as a Means Towards Understanding Finnish Family Farmers' Perceptions of Success

This study investigates the classification of the family farmers' perceptions of success, based on characteristics and resources. The empirical analysis was undertaken on primary data collected via a questionnaire completed by family farmers in Finland. The most important variables in the classification are identified using the C5.0 decision tree algorithm. The algorithm performs with an approximately 16% error rate. In the classification of family farmers' perceptions of success, farm characteristics are of minor importance, whereas the most important variables relate to resources and skills. The most important variables classifying perceptions of success are skills for exploiting opportunities, funding opportunities, and technology, machinery and equipment. The importance of the factors of resources (capital, capability, organisational, skills) are interpreted, together with factors of success (financial, self-realisation, growth and family). This study provides a further indication of the potential of the methodology to highlight the role played by farm characteristics and resources in family farm success.

Keywords: family farm, success, farm characteristics, resources, classification

JEL classification: Q12.

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Introduction

Successful strategies are a driving factor for economic and social sustainability, and this is especially so for family farms. The entrepreneurial strategies implemented by family farms can also contribute to the development of sustainable rural entrepreneurship. Determining what accounts for the success of family farmers is important for theoretical and practical discourses, as well as for understanding future-oriented strategies such as those related to innovation, sustainability and succession (Suess-Reyes and Fuetsch, 2016). Knowledge of the dynamics of successful farming is vital for the sustainability of the rural population.

However, not all farms are the same. Farms are considered to have a range of characteristics and individual farmers have distinct perceptions of success. Likewise, resources used in a strategy for success vary from farm to farm, as farms and farmers have been in a fundamental transitional period requiring resources and trade-offs between efficiency and adaptability with a view to the farm sustainability (Darnhofer *et al.,* 2010). Small farms in particular are considered to be in need of vital policy support to avoid sociological risks affecting the future of rural areas (Hazell *et al.,* 2010). In general, the agricultural sector has its own unique characteristics and structures that distinguish it from other sectors in most parts of the world. Identifying the profile of a typical successful farmer is challenging because the sector is so heterogeneous (McElwee, 2008).

Rather than there being a broad goal of business success, farmers have different objectives and motivations, prioritised in ways that match the characteristics and resources of the farm. Internal and external relations of production have also shaped the definition of business structures and farm typologies (Whatmore *et al.,* 1987). The farm typologies in Europe have been studied from various perspectives (Weltin *et al.,* 2017; Guiomar *et al.,* 2018; Guarin *et al.,* 2020), mostly considering specific farm characteristics. For example, heterogeneity among farmers has been explained from an identity perspective (Vesala *et al.,* 2007; Vesala and Vesala, 2010; Stenholm and Hytti, 2014), comparing entrepreneurial identities rather than creating a new typology of farmers. The focus has been more on behaviour than characteristics, which Gartner (1988) also suggested might be a useful approach in small business and entrepreneurship research.

In the agricultural sector, the most typical business type is family farming. Family farms account for more than 90% of the agricultural businesses in the world (FAO, 2014; Lowder *et al.,* 2021) and in Europe (Eurostat, 2022). In Finland, approximately 84% of agricultural and horticultural enterprises with a financial size exceeding €2,000 are family-operated (LUKE, 2024). In the literature, family firm identification has been mostly based on ownership and self-definition (Casillas *et al.,* 2021) or reliance on family labour more broadly (Garner and De la O Campos, 2014).

A farm business comprises two main elements: the farm and the farm family, inseparably. However, the family farming concept is distinct from conventional farm business terminology (Gasson *et al.,* 1988). What does success mean for family farmers, and what is a successful family farm? Addressing these questions requires a special research setting, by taking the perspective of the farm as a family business into account. The heterogeneity of family businesses and the interrelation between goals and resources at the firm level has been discussed from both entrepreneurship and strategic management perspectives (Chrisman *et al.,* 2013). Farmers value the image of a 'successful farmer' (Walter, 1997). Additionally, Etumnu and Gray (2020) demonstrate the diverse perceptions of success among farmers, highlighting the need for multidimensional measurements, despite their research not focusing on the family unit as such.

Success is usually interchangeably used with such concepts as performance. However, success does not reflect only objective measures, but can also include subjective perceptions (Wach *et al.,* 2020; Fisher *et al.,* 2014; Baron and Henry, 2011; Gorgievski *et al.,* 2011), especially for family farms (Mäkinen *et al.,* 2009). It is not always possible to conceptualise and measure objective performance for family farms, for which the perception of success is more focused on continuity in the family and survival, unlike in other sectors. In addition, objective indicators are not always available. It is of interest to this study how farm characteristics and resources are related to multidimensional perceptions of success, specifically with taking the subjective perceptions of farmers into consideration as a novelty in its theoretical framework.

Besides traditional methods such as regression and correlation-based analysis, there are recently-developed data-driven methods and techniques. Classification algorithms are among those which current developments in data science allow to be used as the techniques of data mining and machine learning. These techniques have been applied in agricultural research (Liakos *et al.,* 2018). There has been a trend in the usage of the techniques by studies focusing on the management of crops (Van Klompenburg *et al.,* 2020), water (El Bilali *et al.,* 2021), soil (Diaz-Gonzalez *et al.,* 2022), livestock and dairy farms (Shine and Murphy, 2022), aquaculture and fisheries (Gladju *et al.,* 2022), agricultural and biological engineering (Huang *et al.,* 2010), and supply chain (Sharma *et al.,* 2020; Kumari *et al.,* 2023). Even though there have been studies from an economic and sociological perspective on risk management (Ghaffarian *et al.,* 2022), decision-making (Attonaty *et al.,* 1999), and farmer typology (Graskemper *et al.,* 2021), the literature is limited in respect of strategic management and successful farm entrepreneurship. The range of studies in the agricultural economics literature that use these techniques with primary datasets has not been wide, except for those models which have been applied on panel datasets (Hyvärinen, 2016). The literature thus far on strategic management and successful entrepreneurship in family farm research lacks studies which outline classification algorithms in detail.

Family farms have unique characteristics and resources in creating a strategy, especially through exploiting the clusters of opportunities (De Rosa *et al.,* 2019). The most important characteristics of family businesses in general also relate to the resources (Alonso and Austin, 2016). And in defining what makes a farm successful in comparison to their counterparts strategically, one of the most common frameworks that has been used in family farm business research is resource-based theory (RBT), which considers the farm as a set of resources that may or may not count as being strategically relevant to its success. RBT has been a trending framework since the early 2000s (Chrisman *et al.,* 2010), but the origin of the theory dates back to Penrose's 'Theory of the Growth of the Firm' in 1959 (Penrose, 2009), and thereafter it has developed further explanations of the critical resources for competition (Wernerfelt, 1989), in addition to the capabilities (Peteraf and Barney, 2003; Teece, 2007), and strategic resources (Barney, 1991) that are considered to be valuable, rare, imperfectly imitable, and non-substitutable. Ultimately, some resources are strategically significant, and this is especially so for family farms. While resources are vitally important for successful strategies, an abundance of resources does not necessarily guarantee that a given business will have a competitive advantage (Mosakowski, 2017; Armstrong and Shimizu 2007). Acknowledging the non-linear and complex nature of the relationship between farm success and resource availability, this study employs an exploratory approach to identify the resources most salient to farmers' perceptions of success.

The aim of this study was to determine whether family farmers can be classified according to how they perceive their success, using farm characteristics and resources as classification variables in machine learning models. In our case, success and resource variables include farmers' perceptions, in other words, their own assessment of success in relation to physical, financial, organisational and skill resources in comparison to their counterparts. In addition to empirical results, our aim with this study was to provide insights into the potential use of machine learning and data mining techniques in the family farm context. As these techniques have not yet been widely used in farm management research, this study introduces a new approach for classification purposes in this area. It also aims to evaluate the efficacy of machine learning as a tool for discerning structures within large datasets of family farm data.

Material and Methods

The questions processed in this study were formulated so as to integrate concepts from both farming and business domains. We updated the questions regarding farm characteristics, which were originally developed by Vesala and Peura (2002) and further specified by Rantamäki-Lahtinen (2009) along with the resources as being suitable for reflections on family farms in Finland. Farm characteristics constructed in this study included several concepts and were grouped into two for each for classification procedure to be more efficient. The characteristics are the use of external labour, whether the type of farm is private or is a company, whether farm was handed down by the family or purchased from a non-family source, whether the farm size under cultivation is lower or higher than the average in Finland, whether there are other business activities, whether the primary production is grain farming, whether there is another family member (aged over 18) in the household, whether there is a child(ren) in the household, whether the current situation of the farm business is stable, whether there is consideration of a long term exit or generational change, whether the farm has organic farming, whether the farmer's education is related to agriculture, whether the farm is located in southwestern or central Finland, and whether the education level is practical experience/short courses or academic-level education.

Resources were considered to be based on European and Finnish farmers' perspectives, and were derived mainly from Forsman (2004), Rantamäki-Lahtinen (2009) and de Wolf *et al.* (2007), which have been constructed as potential resources to lead to a competitive advantage of the farm in the resources of buildings, funding opportunities, profitability, business competence, technology, machinery and equipment, customer relationship management, networks of entrepreneurs, professionalism and networks of other family members, cooperation partners, quality of products and services, organisational culture, production technical skills, financial management skills,

skills for exploiting opportunities, strategic planning and implementation skills and collaboration/networking skills.

Subjective perceptions of success were constructed using suitable measures of small businesses derived from Reijonen and Komppula (2007). These are the perceptions of the best possible financial result, maintaining an adequate standard of living for the farmer and farmer's family, financial profitability of the operation, self-determination in farmer's work, pride in what the farmer does, personal satisfaction, reputation, using the latest technology, keeping the farm business under family control, transferring the business to the next generation, farm size growth and revenue growth. The construction of the variables in the concepts of farm characteristics, resources and success are presented in Appendix 1.

The data were gathered through an electronic survey responded to by Finnish farmers, and the respondents were chosen by the random sampling method. The family farm dataset was filtered with self-assessment of the farmers to the question 'Which of the following best describes your farm business?' with 'We have a family business in which two or more family members are responsible for running the farm'. After data processing, observations from 910 responses from family farmers were included in the analysis. Since there was a high variance for variables about the farm characteristics, they were aggregated into two-level categories before the analysis. Resources and success variables were constructed with 5-point Likert scale (self-assessment of resources between 'much worse' and 'much better', self-rating of skills between 'weak' and 'excellent', and self-assessment of success between 'not at all' and 'very well').

Table 1 presents the distribution of the percentages regarding the farm characteristics of the sample. External labour is hired by 20.8% of family farms, while 79.2% do not hire. The business form of 93.9% of the family farms is the private type and 88.4% of family farms were acquired from the family, as a continuation of the operation of the family business. About 63.5% of family farms are of a smaller size than the average farm size in Finland, which is 51.15 ha (LUKE, 2021), whereas 36.5% are larger than the average. No other business activity is carried out in 70.8% of family farms, but in 29.2% there is. Cereal, grain and other crop production are the main production lines in 56% of family farms, while 44% have other agricultural production such as dairy, milk or other cattle or animal, mixed production, or open field horticulture. There is no other family member(s) (aged over 18 years) in the household in 70.8% of family farms, where 29.2% have at least one other family member(s) (aged over 18 years) in the household. There is no child in the household in 58.2% of family farms, but there is at least one child in the household in 41.8%. The current situation of 54.4% of family farms is stable, while 45.6% of family farms have different situations, such as being in a starting, changing, growing or declining phase. In 67.8% of family farms, there is no consideration of stopping farming or generational change in the next 5 years, while 32.2% consider. 86% of family farms do not practise organic farming, but 14% practise it. Vocational training of 62.4% of farmers in family farm is related to the current business, whereas 37.6% of farmers' education is not related. Over 79% of family farms are located in the provinces in southern or central Finland, while 20.8% are located elsewhere in Finland.

Table 1: Descriptive statistics regarding the farm characteristics.

Variable	Levels	Frequency	Percentage (%)
External labour	Yes	132	20.8
	No	504	79.2
Private or company	Private	597	93.9
	Company	39	6.1
The farm was handed down by the family or purchased from a non-family source	Family	562	88.4
	Elsewhere	74	11.6
The farm size under cultivation	Smaller	404	63.5
	Larger	232	36.5
Other business activities	No	450	70.8
	Yes	186	29.2
Primary production	Cereal, grain and other crop production	356	56.0
	Other agricultural production (dairy, milk or other cattle or animal, mixed production, or open field horticulture)	280	44.0
Other family member(s) (aged over 18 years) in the household	No	450	70.8
	Yes	186	29.2
Child(ren) in the household	No	370	58.2
	Yes	266	41.8
Current situation of the farm business	Stable	346	54.4
	Other (starting, changing, growing or declining)	290	45.6
Long term exit or generational change	No	431	67.8
	Yes	205	32.2
Organic production	No	547	86.0
	Yes	89	14.0
Relatedness of education	Yes	397	62.4
	No	239	37.6
Location	Southwestern and Central Finland	504	79.2
	Elsewhere	132	20.8
Education	At least at practical/short courses or higher	395	62,1
	Academic	241	37.9

Source: own composition

Table 2: Descriptive statistics regarding family farmers' perceptions of their resources in comparison to their counterparts.

Variable	Mean	Standard Deviation
Buildings	3.0	1.1
Funding opportunities	3.4	1.0
Profitability	3.2	0.9
Business competence	3.5	0.9
Technology, machinery and equipment	3.0	1.0
Customer relationship management	3.5	0.8
Networks of entrepreneurs	3.4	0.9
Professionalism and networks of other family members	3.4	0.9
Cooperation partners	3.4	0.7
Quality of products and services	3.6	0.8
Organisational culture	3.4	0.8
Production technical skills	3.8	0.6
Financial management skills	3.7	0.7
Skills for exploiting opportunities	3.5	0.8
Strategic planning and implementation skills	3.5	0.8
Collaboration/networking skills	3.5	0.8

Source: own composition

Table 3: Descriptive statistics regarding family farmers' perceptions of success.

Variable	Mean	Standard Deviation
Best possible financial result	3.0	0.9
Maintaining an adequate standard of living for farmer and farmer's family	3.2	1.1
Financial profitability of the operation	3.1	1.0
Self-determination in farmer's work	3.9	0.9
Pride in what the farmer does	3.8	1.0
Personal satisfaction	3.6	1.0
Reputation	3.6	1.0
Using the latest technology	2.7	1.0
Keeping the farm business under family control	4.0	1.1
Transferring the business to the next generation	3.3	1.3
Farm size growth	2.9	1.3
Revenue growth	2.9	1.2

Source: own composition

The education level of 62.1% of the family farmers is at least at practical/short courses or higher, and 37.9% have academic levels of education.

Additionally, Table 2 and Table 3 represents the mean values and standard deviations regarding the variables of resources and success. In general, family farmers assess their resources and success as being above average.

Classification of the multiple success items is handled using classification algorithms based on data mining and machine learning techniques. The most influential classification algorithms have been discussed in Wu *et al.* (2008). To group the perceptions of success according to farm characteristics and resources, decision tree learning algorithms (Kotsiantis, 2014) were considered. The most common classification methods are Classification and Regression Trees (CART) (Breiman *et al.*, 1984; Loh, 2014), Chi-squared Automatic Interaction Detector (Kass, 1980), C4.5 and C5.0 (Quinlan, 1996) and Random Forest (RF) (Breiman, 2001; Biau and Scornet, 2016). Among the options offered by the algorithms, we used C5.0 algorithm in this study. C5.0 has similarities with other algorithms, but it differs in the splitting procedure of categorical variables, and the objective of the algorithm is to develop a single tree. In addition, the C5.0 algorithm has multiway splitting technique instead of binary. This algorithm was chosen in line with the initial analysis of Hodges-Lehmann Median differences (Hodges and Lehmann, 1963) on error rates, comparing the performance of such algorithms (Appendix 2) and its suitability for the context of this study including the multiplicity of items. For our dataset, C5.0 performed significantly lower error rates comparing to, for example, CHAID and RF.

C5.0 is a decision tree-based classification algorithm, an extended version of C4.5 presented by Quinlan (1996). The algorithm follows the split selection process based on the information gain (Forman, 2003). The aim of the algorithm is to maximise the information gain. Information gain is obtained by the calculation of expected information requirement (Quinlan, 1986), which, in contrast, is minimised to reach the aim. The formula for information gain (1) and entropy (2) is presented as follows:

$$Information\ Gain(Sample, Attribute) = H(Sample) - H(Sample|Attribute) \quad (1)$$

$$Entropy(Sample) = H(Sample) = -\sum_{i=1}^{m} p_i log_2^{p_i} \quad (2)$$

We evaluated the accuracy of the classification using the indicators of error measured in the algorithms, where p_i denotes the proportion of the number of those values occurred in the class *i*. In line with other algorithms, the indicators of error (error rates hereafter), which correspond to the proportion of misclassified observations in the estimations, are calculated to evaluate the accuracy of the algorithm:

$$Accuracy = (TP/TI) \times 100$$
$$Error\ rate_i = (1 - Accuracy_i)$$

where *TI* is the number of total instances, and *TP* is the number of correctly classified instances. In other words, the robustness criterion for the algorithm was set as the error rates in the classifications.

In the estimation, farm characteristics and resource variables were identified as features, and success variables as targets. For each target, C5.0 built one tree. We also examined the structure of the classification and the role that features play in the classification of each target. We formulated the features, farm characteristics, and resources together in the classification procedure. There was only one exception that to avoid overfitting, as also they have very similar meanings in survey language, the profitability resource was excluded from the classification procedure of the first three success variables. The ratios of the trained datasets located in the terminal nodes were calculated, and the feature variables were sorted by their percentages to determine the variables that have the highest importance in the classifications. For further implications, the cross-validation process was held to gain insights on the generalisability of the classification. The process includes the splitting of the data as training and test subgroups (Quinlan, 1996), which in our case, were set to be 70% to 30%, respectively. The algorithm was run in R Project (Version 4.2.3) using *C50* package (Kuhn and Johnson, 2013).

Results

Error rates of the classifications of success variables are presented in Table 4. Success based on farm characteristics and resources is misclassified, with the percentages varying from 13.2% to 18.9%. The lowest error rate results in the classification of the success perception in the operation's financial profitability. The highest error rate is in the classification of the perception of success in keeping the farm business under family control. In general, there are no remarkable differences between the accuracy of the classifications of the perceptions of success of family farmers based on the farm characteristics and resources. Around 84% of the cases are classified correctly using the C5.0 algorithm.

Variables' levels of importance of farm characteristics and resources in classification of family farmers' perceptions of success are reported in Appendix 3. In general, farm characteristics have minor importance in classifications of family farmers' perceptions of success.

Table 5 presents the variables' levels of importance regarding the classification of family farmers' perceptions of success. The five highest and lowest levels of importance are sorted for each success variable. The best possible financial result is classified mostly by production technical skills, skills for exploiting opportunities, technology, machinery and equipment, private or company type of the farm, professionalism and networks of other family members, while in classification of best possible financial result, whether there are other business activities, whether the location of the farm is southwest and central Finland, collaboration/networking skills, whether the current situation of the farm business is stable, quality of products and services have the lowest levels of importance. Maintaining an adequate standard of living for the farmer and farmer's family is classified mostly by skills for exploiting opportunities, funding opportunities, technology, machinery and equipment, collaboration/networking skills, production technical skills, while the lowest levels of importance in classification corresponds to cooperation partners, whether the education level is practical experience/short courses or academic-level education, existence of children in the household, whether the primary production is grain farming, organisational culture. Financial profitability of the operation is classified mostly by funding opportunities, strategic planning and implementation skills, collaboration/networking skills, skills for exploiting opportunities,

Table 4: Error rates regarding the classifications of success variables.

Success variable	Error rate (%)
Best possible financial result	16.4
Maintaining an adequate standard of living for farmer and farmer's family	16.7
Financial profitability of the operation	13.2
Self-determination in farmer's work	17.3
Pride in what the farmer does	16.5
Personal satisfaction	17.3
Reputation	15.3
Using the latest technology	15.1
Keeping the farm business under family control	18.9
Transferring the business to the next generation	15.9
Farm size growth	17.1
Revenue growth	17.6

Source: own composition

production technical skills, but the lowest levels of importance in classification belong to buildings, whether there are other business activities, private or company type of the farm, whether the farm has organic farming, whether the primary production is grain farming.

Self-determination in a farmer's work is classified mostly by production technical skills, funding opportunities, organisational culture, collaboration/networking skills, whether there is consideration of long term exit or generational change, while the variables with the lowest levels of importance are customer relationship management, whether there are other business activities, whether a farm was handed down by the family or purchased from a non-family source, private or company type of the farm, existence of children in the household. Pride in what the farmer does is classified mostly by collaboration/networking skills, organisational culture, skills for exploiting opportunities, quality of products and services, funding opportunities, but the lowest levels of importance correspond to whether there is a consideration of long term exit or generational change, whether the farm has organic farming, whether the farmer's education is related to agriculture, existence of children in the household, whether the primary production is grain farming. Personal satisfaction is classified mostly by collaboration/networking skills, quality of products and services, cooperation partners, strategic planning and implementation skills, financial management skills, while the lowest levels of importance in classification belongs to whether the location of the farm is southwest and central Finland, professionalism and networks of other family members, whether there is a consideration of long term exit or generational change, whether the current situation of the farm business is stable, whether the farm size under cultivation is lower or higher than average in Finland. Reputation is classified mostly by funding opportunities, quality of products and services, organisational culture, collaboration/networking skills, strategic planning and implementation skills, but the lowest levels of importance come from

Table 5: Variables with the highest and lowest variable levels of importance for classification of success.

Success variable	Highest	%	Lowest	%
Best possible financial result	sk1	100	c5	0.9
	sk3	89.5	c13	3.0
	r5	61.8	sk5	3.5
	c2	36.7	c9	3.9
	r8	35.5	r10	5.0
Maintaining an adequate standard of living for farmer and farmer's family	sk3	100	r9	0
	r2	91.4	c14	2.0
	r5	74.4	c8	4.4
	sk5	68.1	c6	6.8
	sk1	52.7	r11	6.9
Financial profitability of the operation	r2	100	r1	1.6
	sk4	85.69	c5	2.2
	sk5	76.26	c2	3.6
	sk3	47.64	c11	4.7
	sk1	38.84	c6	9.1
Self-determination in farmer's work	sk1	100	r6	1.26
	r2	91.82	c5	1.42
	r11	91.82	c3	1.73
	sk5	37.74	c2	1.89
	c10	36.64	c8	1.89
Pride in what the farmer does	sk5	100	c10	0.63
	r11	88.99	c11	3.77
	sk3	85.69	c12	4.09
	r10	65.72	c8	6.13
	r2	45.6	c6	7.39
Personal satisfaction	sk5	100	c13	0
	r10	92.3	r8	0
	r9	82.08	c10	2.2
	sk4	78.77	c9	2.67
	sk2	68.87	c4	3.62
Reputation	r2	100	r8	0.94
	r10	97.33	r4	2.04
	r11	83.96	c9	4.87
	sk5	82.7	c12	5.19
	sk4	59.12	c14	7.55
Using the latest technology	r5	100	c11	2.52
	sk3	100	sk1	2.83
	r2	67.14	c8	3.14
	r4	55.19	c12	3.93
	r8	46.7	c14	3.93
Keeping the farm business under family control	sk5	100	c2	0
	r8	84.75	c3	1.26
	r11	57.7	c6	1.57
	r4	43.87	sk3	2.67
	sk2	41.35	c10	3.46
Transferring the business to the next generation	sk1	100	c8	2.36
	sk5	96.86	c8	3.93
	sk3	87.58	r9	4.4
	r3	84.91	r10	8.18
	c11	58.81	c1	9.28
Farm size growth	r3	100	c11	0
	r5	79.72	sk4	3.3
	sk1	75.31	c9	5.5
	r4	56.29	r11	5.82
	r8	53.14	c10	7.23
Revenue growth	sk3	100	c12	0.94
	r3	91.35	c8	1.1
	r9	75.47	sk4	1.1
	r2	75.16	sk1	1.26
	r8	60.22	c8	3.14

Note: c1: existence of external labour, c2: private or company type of the farm, c3: whether a farm was handed down by the family or purchased from a non-family source, c4: whether the farm size under cultivation is lower or higher than average in Finland, c5: whether there are other business activities, c6: whether the primary production is grain farming, c7: existence of other family member(s) (aged over 18 years) in the household, c8: existence of children in the household, c9: whether the current situation of the farm business is stable, c10: whether there is a consideration of long term exit or generational change, c11: whether the farm has organic farming, c12: whether the farmer's education is related to agriculture, c13: whether the location of the farm is southwest and central Finland, c14: whether the education level is practical experience/short courses or academic-level education. r1: buildings, r2: funding opportunities, r3: profitability, r4: business competence, r5: technology, machinery and equipment, r6: customer relationship management, r7: networks of entrepreneurs, r8: professionalism and networks of other family members, r9: cooperation partners, r10: quality of products and services, r11: organisational culture, sk1: production technical skills, sk2: financial management skills, sk3: skills for exploiting opportunities, sk4: strategic planning and implementation skills and sk5: collaboration/networking skills

Source: own composition

professionalism and networks of other family members, business competence, whether the current situation of the farm business is stable, whether the farmer's education is related to agriculture, whether the education level is practical experience/short courses or academic-level education.

Using the latest technology is classified mostly by technology, machinery and equipment, skills for exploiting opportunities, funding opportunities, business competence, professionalism and networks of other family members, while the variables with the lowest levels of importance are whether the farm has organic farming, production technical skills, existence of children in the household, whether the farmer's education is related to agriculture, whether the education level is practical experience/short courses or academic-level education.

Keeping the farm business under family control is classified mostly by collaboration/networking skills, professionalism and networks of other family members, organisational culture, business competence, financial management skills, but the lowest levels of importance correspond to private or company type of the farm, whether a farm was handed down by the family or purchased from a non-family source, whether the primary production is grain farming, skills for exploiting opportunities, whether there is a consideration of long term exit or generational change. Transferring the business to the next generation is classified mostly by production technical skills, collaboration/networking skills, skills for exploiting opportunities, profitability, whether the farm has organic farming, while the lowest levels of importance come from existence of children in the household, existence of children in the household, cooperation partners, quality of products and services, existence of external labour.

Farm size growth is classified mostly by profitability, technology, machinery and equipment, production technical skills, business competence, professionalism and networks of other family members, while the lowest levels of importance belong to whether the farm has organic farming, strategic planning and implementation skills, whether the current situation of the farm business is stable, organisational culture, whether there is a consideration of long-term exit or generational change. Revenue growth classified mostly by skills for exploiting opportunities, profitability, cooperation partners, funding opportunities, professionalism and networks of other family members, while the variables with the lowest levels of importance are whether the farmer's education is related to agriculture, existence of children in the household, strategic planning and implementation skills, production technical skills, existence of children in the household.

Methodological Implications

This study provides a classification framework using the C5.0 algorithm among machine learning and data mining techniques. The results of the semi-supervised estimations were interpreted in accordance with the error rates, reflecting the accuracy of the algorithms, and therefore, how the algorithm performed in turn.

The algorithm might be further developed. Accuracy of the algorithm might be increased by further supervision, by bagging (Breiman, 1996), and boosting (Freund and Schapire, 1997) using C4.5 algorithm (Quinlan, 1996), winnowing or other approaches in training the data and building trees (Kuhn and Johnson, 2013). It must be noted that while the training accuracy is high, cross validation accuracy is low, which addresses the lack of generalisability of the conceptual model, due to potential overfitting issues. For similar data to that used here, which has somewhat concentrated frequencies in favour of some levels or medians, or variables that have more levels, a particular algorithm might be developed by weighting options (Ting, 2002) or adjusting misclassification costs. In that case, one might consider adjusting the error-based classifiers so that they become more cost-sensitive (Breiman *et al.,* 1984; Domingos, 1999). Likewise, as offered by the software, tuning options could be used. Alternatively, algorithms other than C5.0 could be employed – indeed, a comparison between alternative algorithms would be insightful.

Implications for Success Factors of Family Farmers

As indicated in the results, elements of perceptions of success in our study are concentrated within dimensions. To improve the classification performance, we used dimension reduction by applying Confirmatory Factor Analysis (Kline, 2023) as an alternative approach to pre-process the target variables to be used in classification procedure.

The factor structure was used in line with the same conceptualisation used by Yigit *et al.* (2024), whereby perceptions of success of family farmers are conceptualised as latent variables identified as economic, self-realisation, growth and family control, as are resources, taken to be capital, capability, organisational and skills (Figure 1). All success factors were found to be significant in the model, whose composite reliability and average variance extracted scores indicate that the model is reliable and valid. In the next step, the standardised loadings of each latent success variables were categorised into three; to be low, medium and high. It was determined that interpretation of the classification of latent success constructs would be also changed. Since the target variables are not observed but are constructs, and the categorisation explains the level of determination of the variance in those constructs, this procedure can be explained as the classification of the different levels of varying success constructs based on the characteristics and resources.

This study used a classification method which explored the relationships between variables from a non-causal perspective. This means that the interpretation of the analysis might show similarities, especially with correlation analysis. However, there are differences as well. To begin with, this method was more flexible compared to correlation analysis, an approach that requires assumptions such as linear dependency. However, this method does not indicate the direction of the relationships as simply as correlation method would, which makes the explanation of the results more complicated. Furthermore, interpretation of the results would be more complex if the data were pre-processed, even if there

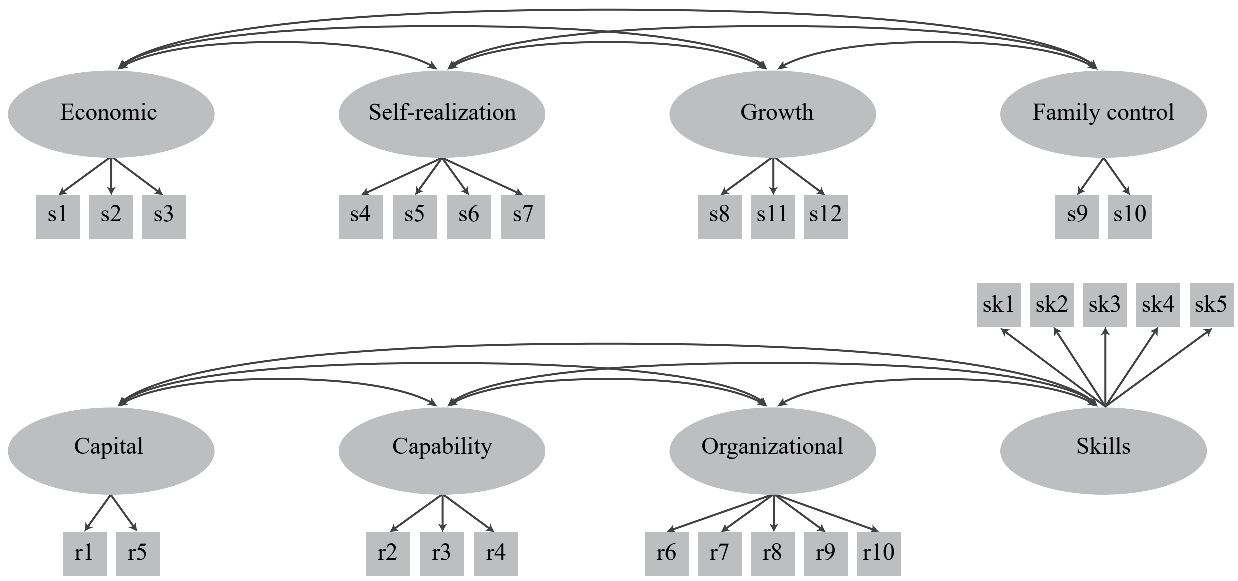

Figure 1: Factors of resources and success.

r1: buildings, r2: funding opportunities, r3: profitability, r4: business competence, r5: technology, machinery and equipment, r6: customer relationship management, r7: networks of entrepreneurs, r8: professionalism and networks of other family members, r9: cooperation partners, r10: quality of products and services, r11: organisational culture, sk1: production technical skills, sk2: financial management skills, sk3: skills for exploiting opportunities, sk4: strategic planning and implementation skills and sk5: collaboration/networking skills, s1: best possible financial result, s2: maintaining an adequate standard of living for the farmer and farmer's family, s3: financial profitability of the operation, s4: self-determination in farmer's work, s5: pride in what the farmer does, s6: personal satisfaction, s7: reputation, s8: using the latest technology, s9: keeping the farm business under family control, sl0: transferring the business to the next generation, s11: farm size growth and s12: revenue growth.

Source: own composition

was a development in cross validation, as occurred in this study (Appendix 4). Further factorisation could simplify the classification process using the most important variables in the initial analysis, which in our case related to resources and skills, and in our case the simplification results in the observation that the most important factors are capabilities and capital (Appendix 5). However, it must be noted that we noticed a trade-off caused by the simplification, namely that it still increases the cross validation (Appendix 6) but it also limits the information to be interpreted.

Making it different from correlation analysis, this method provides performance measures. Instead of testing only the significance of the correlational relationship, this method provides the potential to monitor and develop the performances. Eventually, the data mining techniques could be challenging when using categorical data, such as in this study. However, the continuation of the efforts to develop the performance of the estimation is required in the literature (Maione *et al.,* 2019), especially when working with social data. Even though the overall performance of the classification algorithm in this study is still far from perfect, a fact which limits the generalisability of the results, we think it would be important to monitor the performance of the method of analysis.

Implications for Farm Characteristics and Resources

Most of the farm characteristics have only lower levels of importance in the classification of family farmers' perceptions of success. Although the characteristics of the farm and farmer influence management (Rikkonen *et al.,* 2013), we found that the characteristics in our study were not very important when classifying family farmers' perceptions of success. The existence of external labour and private or company type of farm are of minor importance, but they are involved in classification of several perceptions of success.

The existence of external labour has relatively low but a wide range of levels of relevance with the perceptions of success of family farmers. Hired external labour is an indicator of heterogeneity of goals among family farms, as it is a catalyst of technical efficiency especially in dairy sector in Europe (Garcia-Covarrubias *et al.,* 2024). The demand to use technological innovations, enhance the production capacity, support the family labour and intention to grow seem to diversify the perceptions of success and strategies of Finnish family farmers for hiring external labour.

Similarly, private or company type of the farm is relevant to several perceptions of success with minor importance, especially with farm size growth. Whether there is consideration of a long-term exit or generational change is of little importance in classification of self-determination. This touches on the potential structural changes related to the different decision-making processes in family farms, about which we can point out the discrepancy between the subjective perceptions of entrepreneurs on short-term changes in wellbeing and long-term plans (Dijkhuizen *et al.,* 2018). Speaking of structural changes, whether the farm has organic farming has moderate importance in the classification of transferring the business to the next generation, and in general in family control success. This is in line with Väre *et al.* (2021) on the succession plans of organic farms in Finland. And for all family farms in Finland, we found that whether the location of the farm is in the southwest or central part of the country is also of little importance in the classification of using the latest technology. Whether a farm was handed down by the family or purchased from a non-family source has also low importance in several perceptions of success, especially revenue growth, which would be of interest to new entrants to the agricultural sector who already have a family background in farming.

In addition, this study found that some characteristics are not important in the classification of perceptions of success. Whether the farm size under cultivation is lower or higher than average in Finland, whether there are other business activities, whether the primary production is grain farming, the existence of other family member(s) (aged over 18 years) in the household, the existence of children in the household, whether the current situation of the farm business is stable, whether the farmer's education is related to agriculture, whether the education level is practical experience/short courses or academic-level education, are the characteristics that were not found to be important in the classification of family farmers' perceptions of success. These results would bring reconsideration of the framework that family characteristics could be implemented as dimensions of RBT (Habbershon and Williams, 1999), perhaps by using family capital (Danes *et al.,* 2009). It can also be suggested that more agrobusiness-related characteristics of family farms can be included as factors such as investments and variety of plant cultivation in more agriculture related decisions such as the use of fertilisers (Besuspariene and Niskanen, 2020), especially to give insights in addition with an agricultural policy dimension.

In a way other than the farm characteristics, most of the resources are important in classifying family farmers' perceptions of success. The most important variables in classification of success are found to be skills for exploiting opportunities, funding opportunities, and technology, machinery and equipment. To start with, the most vital resource feature in classification is skills for exploiting opportunities. Skills for exploiting opportunities are especially important in all economic and self-realisation related success, along with using the latest technology, revenue growth, pride in what as farmer does, transferring the business to the next generation, and a little in personal satisfaction and reputation. Unlike simply identifying opportunities (Pindado *et al*., 2018), 'skills for exploiting opportunities' imply a proactive managerial approach crucial for family farm success, emphasising the need for further research into farmers' strategic thinking (Mäkinen, 2013). Within this study, we define success as reflecting both the micro level, which is the profitability of individuals and households, and conversely, the macro level, which is business growth and achievement, as demonstrated by the skills for exploiting opportunities. We label this interpretation as 'having a profitability resource in the family farm while at the same time having the skills to exploit opportunities in the outside/business world'.

Funding opportunities are crucial for economic success, reputation, and revenue growth. They also contribute to reputation and self-determination, though to a lesser extent, economic stability. This suggests farmers may leverage funding opportunities as a form of social capital, as noted by Sutherland and Burton (2011), providing both practical resources and a sense of security. However, it is important to note that, while funding is important for self-realisation, it has limited impact on growth success beyond revenue.

Technology, machinery, and equipment are crucial for adopting the latest technology and maintaining family control of the farm business. This finding aligns with research highlighting the link between sustainable family business innovation and technological integration (Labaki and Haddad, 2019). For family farms, this underlines the importance of generational involvement and leveraging knowledge gained both from the market and from within the family (Fuetsch, 2022). Overall, technology significantly contributes to economic and growth-related success.

This study found that technical production skills, profitability, organisational culture, and collaboration/networking skills significantly impact multiple success perceptions. Notably, profitability plays a complex role in family-related success: it predicts the intention to transfer the business but not to maintain family control, and it contributes to general growth success while not to self-realisation. This seeming contradiction can be explained by the socioemotional wealth (SEW) perspective (Gomez-Mejia *et al*., 2011; Berrone *et al*., 2012), which prioritises non-economic values, a concept particularly pertinent in agricultural (Gómez-Mejía *et al*., 2007) and family farm research (Dressler and Tauer, 2015).

Technical production skills are important in self-determination in farmer's work, transferring the business to the next generation, farm size growth, maintaining an adequate standard of living for the farmer and farmer's family, but also important with the best possible financial result. Even though small-scale family farms are considered to use less machinery in arable farming (Yagi and Hayashi, 2021), technical capital still seems decisive in shaping perceptions about farm growth and survival. In this perspective, new insights on the technical and growth and survival relationship can be studied, using the efficiency of the farm business (Bojnec and Latruffe, 2008), or the conceptualisation of the farmer's concept of a farmer, entrepreneur, rural entrepreneur or a contractor (McElwee, 2008) by focusing on technical and strategic orientation of the family. We note in this study that perceptions of expanding family farms are associated with both financial and technical dimensions. In fact, we argue that technical production skills are vital, as also shown to be important in classification of factors of economic, growth and family control.

Organisational culture significantly influences maintaining family control of the farm, and to a lesser degree, impacts business transfer, revenue growth, and self-realisation. We attribute this to the concentric nature of family farming. While this study cannot determine causality, we propose further investigation through the lens of self-determination theory, exploring the relationship between autonomy, well-being (Markussen *et al*., 2018), and trade-offs with financial rewards (Ocean and Howley, 2023). This finding also provides a foundation for examining family farm resilience, including the intergenerational transfer of culture and experience (Hanson *et al*., 2019; Nuthall, 2009), and the potential for strategic adaptability.

Collaboration and networking skills are essential for emotional and family-related success, with a supporting role in financial outcomes. This reinforces the need to prioritise social relationship development to address farmer stress, well-being, and family-work balance (Kallioniemi *et al*., 2008, 2016; Janker *et al*., 2021; Melberg, 2003; Gorgievski *et al*., 2010; Paskewitz and Beck, 2017). Historically, collaboration has been central to agricultural activities, especially family farming, making social interaction skills critical for emotional success. Meanwhile, other resources, while relevant, have a more focused importance. Buildings primarily classify living standards and profitability. Entrepreneurial networks classify farm expansion and revenue. Professionalism and family networks classify family control along with revenue and pride. Cooperation partners classify personal satisfaction and revenue, with minor importance in farm growth and technology adoption.

Some resources are important in classification of only some perceptions of success, and these resources are business competence, quality of products and services, financial management skills and strategic planning and implementation skills. Business competence is important in farm size growth, using the latest technology and keeping the farm business under family control. Quality of products and services is especially highly important in self-determination and pride, reputation, and a little in keeping the farm business under family control. Financial management skills are moderately important in personal satisfaction. Strategic planning and implementation skills are especially highly important in personal satisfaction, but they are also important in transferring the business to the next generation, and in general, in economic and self-realisation senses of success.

Customer relationship management showed no significant importance in the classification of family farmer success. While the majority of resources were impactful, their importance varied greatly. Some were highly influential in a small number of success measurements, while others provided small amounts of influence across many measurements.

Practical Implications for Successful Family Farming, Agricultural Policy and Rural Development

Classification of the family farmers' perceptions of success vary between success items. We note that the perceptions of success have not been studied widely, so it would be useful to provide some interpretation of the results on the classification. These concepts might be different from other measures, such as performance. In general, perceptions of success are classified most importantly by the resources and skills. Our main interpretation of the results revealing the importance of skills in classification of family farmers' perception of success is that successful family farming is highly related to agricultural entrepreneurship, entrepreneurial skills, plus economic flexibility/opportunities afforded to family farmers, and the development of innovation and technology at a rural level. From a broader perspective, this study also underlines that successful family farming is especially closely related to human and social capital, and capabilities. The two points that we think are important in enhancing the success of family farmers further are summarised below, to provide implications for family farmers, researchers of family farming, and stakeholders in agricultural policy and rural development.

This study measures the perceptions of success of family farmers, in which the dynamics of successful farming are considered in the strategic management of the family farm. Success elements might have different meanings when perceived by the farmers, based on subjective perceptions, such as eliminating obstacles while developing the farm business (Hansson and Sok, 2021), and might be at different levels according to the strategies that farmers have. This may be taken into account when thinking about, monitoring and making policies on strategies for the development of family farms.

The interplay between financial and psychological factors is evident (Heo *et al*., 2020). Integrating the family concept into success classifications introduces greater complexity, yet provides a more nuanced understanding. The query, 'Is success optimised by a particular strategy?' gains a distinct significance when evaluated through the lens of family farm management, given their unique goals, resources, and skills.

Conclusions

Perceptions of success of Finnish family farmers were classified mostly by resources and skills, because farm characteristics do not play key roles in the classification of these. Skills for exploiting opportunities, funding opportunities, and technology, machinery and equipment are among the more important classifiers in perceptions of success of family farmers. While some farm characteristics are important in some of the classifications (such as external labour, private or company type of the farm, consideration of long-term exit or generational change, organic farming etc.), some resources are found to be important in several classifications (e.g. technical production skills, profitability, organisational culture, collaboration/networking skills). Although this study's results are not generalisable, as indicated by the classification algorithm's performance, they highlight the intricate nature of family farmer success perceptions and strategies, where resource influence varies significantly across different success factors.

We hope that the interpretations from the results will be useful for considering perceptions of success of family farmers, and the process of resource development in family farms in line with business strategy, and resource use efficiency. In a broader perspective, this study provides insights to be used in academic and practical efforts in enhancing sustainable rural economic development. As implied in this study, we highlighted the importance of strengthening the social capital of family farmers and farmer groups, as a policy recommendation.

This study has limitations. As mentioned in methodological implications, firstly, that the accuracy rates when classifying the family farmers' perceptions of success are not high. Besides, we employed farm characteristics, resources and skills to classify perceptions of success, which are mostly internal to the farms and farmers. However, some externalities that might classify the perceptions of success importantly as well, such as the influence of climate change and the change in the livelihood on the farm typologies. Besides, we focused on profit maximisation in measuring economic and financial success. However, the framework could be extended by including success measures regarding cost minimisation and survival strategies, which are also important for family farmers. Lastly, this study lacks insights on execution of strategy into practice in family farms.

Further research could perhaps enrich our understanding of the dynamics of family farmers' perceptions of success and farm characteristics and resources. We propose that an interesting approach could be to add characteristics unique to the country's agricultural sector. Studies from a different vision of natural resource management research could focus on, for example forest and water, livestock, forage quality and production, animal welfare, ecotourism, dairy and fisheries. More broadly, changes in socioeconomic, rural, and ecological structures could be considered as well. Furthermore, countries with different socioeconomic conditions and empowerment, institutional conditions, cultural aspects, and different norms in intensity of participation to collective/collaborative actions could be interesting to study. Lastly, a deeper approach considering family structure and the quality of health and wellbeing could also be insightful.

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Appendices

Appendix 1: Construction of the variables.

Variable	Construct
Farm characteristics	2 levels
External labour	use of external labour or not
Private or company	whether the farm is the private or company type
The farm was handed down by the family or purchased from a non-family source	whether farm was handed down by the family or purchased from a non-family source
The farm size under cultivation	whether the farm size under cultivation is lower or higher than average in Finland
Other business activities	whether there are other business activities
Primary production	whether the primary production is grain farming
Other family member(s) (aged over 18 years) in the household	whether there is another family member(s) (aged over 18 years) in the household
Child(ren) in the household	whether there is a child(ren) in the household
Current situation of the farm business	whether the current situation of the farm business is stable
Long-term exit or generational change	whether there is a consideration of long-term exit or generational change
Organic production	whether the farm has organic farming
Relatedness of education	whether the farmer's education is related to agriculture
Location	whether the location of the farm is in southwest or central Finland
Education	whether the education level is practical experience/short courses or academic-level education
Resources	5-levels
Buildings	self-assessment of the buildings of the farm company in relation to other farm companies in the same field
Funding opportunities	self-assessment of the funding opportunities of the farm company in relation to other farm companies in the same field
Profitability	self-assessment of the profitability of the farm company in relation to other farm companies in the same field

Variable	Construct
Business competence	self-assessment of the business competence of the farm company in relation to other farm companies in the same field
Technology, machinery and equipment	self-assessment of the technology, machinery and equipment of the farm company in relation to other farm companies in the same field
Customer relationship management	self-assessment of the customer relationship management of the farm company in relation to other farm companies in the same field
Networks of entrepreneurs	self-assessment of the networks of entrepreneurs of the farm company in relation to other farm companies in the same field
Professionalism and networks of other family members	self-assessment of the professionalism and networks of other family members of the farm company in relation to other farm companies in the same field
Cooperation partners	self-assessment of the cooperation partners of the farm company in relation to other farm companies in the same field
Quality of products and services	self-assessment of the quality of products and services of the farm company in relation to other farm companies in the same field
Organisational culture	self-assessment of the organisational culture of the farm company in relation to other farm companies in the same field
Production technical skills	self-rating of the skills of the people responsible for your farm company as a whole in the production technical skills
Financial management skills	self-rating of the skills of the people responsible for your farm company as a whole in financial management skills
Skills for exploiting opportunities	self-rating of the skills of the people responsible for your farm company as a whole in the skills for exploiting opportunities
Strategic planning and implementation skills	self-rating of the skills of the people responsible for your farm company as a whole in the strategic planning and implementation skills
Collaboration/networking skills	self-rating of the skills of the people responsible for your farm company as a whole in the collaboration/networking skills
Success	5-levels
Best possible financial result	self-assessment of how well the farm has managed to implement the best possible financial result in the farm business
Maintaining an adequate standard of living for farmer and farmer's family	self-assessment of how well the farm has managed to implement the maintaining an adequate standard of living for the farmer and the farmer's family in the farm business
Financial profitability of the operation	self-assessment of how well the farm has managed to implement the financial profitability of the operation in the farm business
Self-determination in farmer's work	self-assessment of how well the farm has managed to implement the self-determination in farmer's work in the farm business
Pride in what the farmer does	self-assessment of how well the farm has managed to implement pride in what the farmer does in the farm business
Personal satisfaction	self-assessment of how well the farm has managed to implement personal satisfaction in the farm business
Reputation	self-assessment of how well the farm has managed to implement a good reputation in the farm business
Using the latest technology	self-assessment of how well the farm has managed to implement using the latest technology in the farm business
Keeping the farm business under family control	self-assessment of how well the farm has managed to implement keeping the farm business under family control in the farm business
Transferring the business to the next generation	self-assessment of how well the farm has managed to implement transferring the business to the next generation in the farm business
Farm size growth	self-assessment of how well the farm has managed to implement farm size growth in the farm business
Revenue growth	self-assessment of how well the farm has managed to implement revenue growth in the farm business

Source: own composition

Appendix 2: Hodges-Lehmann Median Differences.

		Confidence Interval	
	Estimate	**Lower**	**Upper**
CHAID-C5.0	0.25	0.18	0.305
RF-C5.0	0.3	0.23	0.335
RF-CHAID	0.05	0.04	0.06

Source: own composition

Appendix 3: Variables' levels of importance of farm characteristics and resources in classification of perceptions of success.

	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
c1	9.75	26.57	26.57	17.45	13.52	25.16	13.05	11.32	17.45	9.28	26.57	31.13
c2	36.64	19.81	19.81	1.89	35.38	29.56	34.59	25.47	0	37.89	49.21	7.86
c3	10.85	16.19	16.19	1.73	41.19	15.57	32.39	32.7	1.26	11.48	11.95	43.08
c4	9.12	13.36	13.36	10.38	12.58	3.62	9.12	16.82	6.6	11.16	24.06	8.49
c5	0.94	16.67	16.67	1.42	11.48	12.74	27.83	9.59	19.65	25.16	8.96	12.58
c6	5.03	6.76	6.76	20.6	7.39	5.66	13.68	8.65	1.57	20.91	29.25	4.87
c7	10.85	4.4	4.4	23.27	6.13	6.29	16.67	6.45	10.22	3.93	9.59	1.1
c8	7.7	13.05	13.05	1.89	12.58	9.43	11.01	3.14	8.49	2.36	7.23	3.14
c9	3.93	10.69	10.69	5.19	8.02	2.67	4.87	7.55	6.13	10.85	5.5	9.59
c10	5.82	9.59	9.59	36.64	0.63	2.2	16.04	4.09	3.46	20.6	7.23	8.65
c11	16.19	27.83	27.83	10.53	3.77	6.29	11.01	2.52	21.54	58.81	0	12.89
c12	13.05	8.81	8.81	7.55	4.09	8.96	5.19	3.93	12.89	9.91	8.49	0.94
c13	2.99	6.92	6.92	3.77	16.67	0	21.38	43.08	20.44	9.75	20.28	10.38
c14	17.45	2.04	2.04	9.59	22.48	12.11	7.55	3.93	12.89	12.74	9.12	20.6
r1	22.17	26.73	26.73	25.16	11.95	39.31	12.11	13.21	7.55	14.78	30.66	32.23
r2	34.28	91.35	91.35	91.82	45.6	27.04	100	67.14	20.13	21.54	21.38	75.16
r3	*	*	*	7.86	41.51	10.69	35.22	18.24	37.11	84.91	100	91.35
r4	10.69	35.22	35.22	32.55	24.37	25.16	2.04	55.19	43.87	11.01	56.29	25.47
r5	61.79	74.37	74.37	21.54	13.52	33.33	28.62	100	15.72	35.85	79.72	35.22
r6	26.89	23.27	23.27	1.26	16.67	14.47	9.12	13.99	8.33	19.5	9.91	9.59
r7	17.45	26.73	26.73	5.5	18.71	13.05	0.94	10.22	8.65	19.34	53.14	60.22
r8	35.53	34.75	34.75	6.92	27.67	82.08	30.66	40.25	18.87	4.4	42.45	75.47
r9	27.2	0	0	5.66	65.72	92.3	97.33	22.01	30.03	8.18	9.75	46.54
r10	5.03	18.4	18.4	91.82	88.99	15.41	83.96	37.89	57.7	41.98	5.82	40.09
r11	18.24	6.92	6.92	31.76	41.67	0	23.74	46.7	84.75	37.58	30.19	55.66
sk1	100	52.67	52.67	100	43.87	21.23	18.55	2.83	9.91	100	75.31	1.26
sk2	33.96	22.33	22.33	3.3	37.89	68.87	13.99	27.36	41.35	12.11	7.86	26.89
sk3	89.47	100	100	11.79	85.69	41.82	38.36	100	2.67	87.58	12.11	100
sk4	16.35	31.92	31.92	22.96	38.99	78.77	59.12	24.84	8.81	41.67	3.3	1.1
sk5	3.46	68.08	68.08	37.74	100	100	82.7	12.42	100	96.86	14.31	37.89

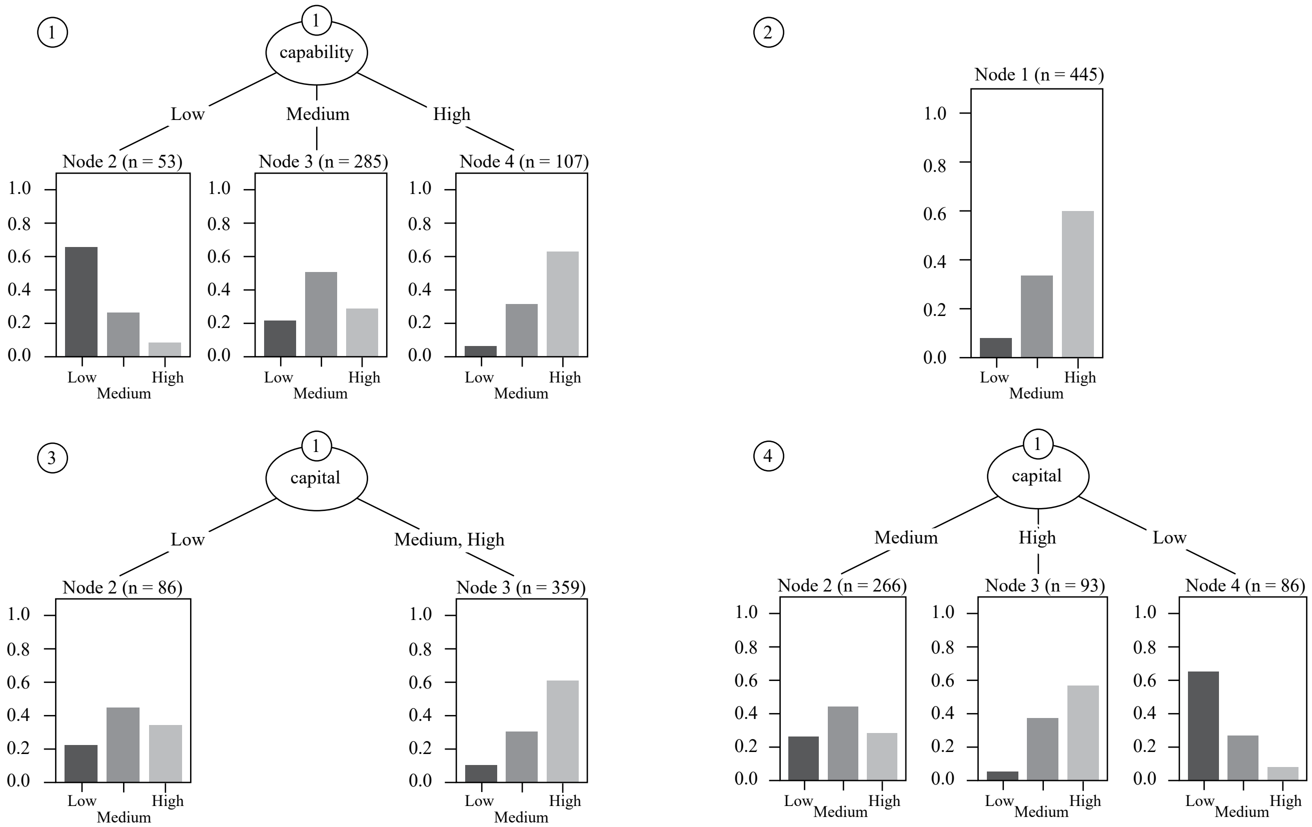
Note: c1: existence of external labour, c2: private or company type of the farm, c3: whether a farm was handed down by the family or purchased from a non-family source, c4: whether the farm size under cultivation is lower or higher than average in Finland, c5: whether there are other business activities, c6: whether the primary production is grain farming, c7: existence of other family member(s) (aged over 18 years) in the household, c8: existence of children in the household, c9: whether the current situation of the farm business is stable, c10: whether there is a consideration of long term exit or generational change, c11: whether the farm has organic farming, c12: whether the farmer's education is related to agriculture, c13: whether the location of the farm is southwest and central Finland, c14: whether the education level is practical experience/short courses or academic-level education. r1: buildings, r2: funding opportunities, r3: profitability, r4: business competence, r5: technology, machinery and equipment, r6: customer relationship management, r7: networks of entrepreneurs, r8: professionalism and networks of other family members, r9: cooperation partners, r10: quality of products and services, r11: organisational culture, sk1: production technical skills, sk2: financial management skills, sk3: skills for exploiting opportunities, sk4: strategic planning and implementation skills and sk5: collaboration/networking skills. s1: best possible financial result, s2: maintaining an adequate standard of living for the farmer and farmer's family, s3: financial profitability of the operation, s4: self-determination in farmer's work, s5: pride in what the farmer does, s6: personal satisfaction, s7: reputation, s8: using the latest technology, s9: keeping the farm business under family control, s10: transferring the business to the next generation, s11: farm size growth and s12: revenue growth
*: excluded from the classification
Source: own composition

Appendix 4: Accuracy rates of the classification of success factors for the cross-validation.

Success factor	Accuracy rate (%)
Economic success	46.60
Self-realisation success	55.50
Growth success	49.21
Family control success	47.64

Source: own composition

Appendix 5: Decision trees for the success factors based on resource factors.



Decision tree plots for the factors of 1: economic success, 2: self-realisation, 3: family, 4: growth
Source: own composition

Appendix 6: Accuracy rates of the classification of success factors using resource factors for the cross-validation.

Success factor	Accuracy rate (%)
Economic success	53.93
Self-realisation success	59.69
Growth success	59.69
Family control success	53.40

Source: own composition

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The Impact of Climate Change on Food Security: Evidence from Panel Data Analysis in Central Asia

Climate change leads to various impacts, including reduced production, lower crop yields, land degradation, soil erosion, and overall, food insecurity. It is projected that by 2080, between 5 million and 170 million people could encounter serious food shortages. Currently, approximately 5 million people are experiencing inadequate access to food in Central Asia. This study investigates the impact of climate change on food security in Central Asia by using panel data analysis for five Central Asian countries between 2000 and 2020. The findings indicate that weather shocks negatively affect food security dimensions. Based on the findings, the authors recommend improving education on adapting the agricultural sector to climate change, implementing technological improvements, and transitioning to sustainable agriculture.

Keywords: food security, vulnerability, climate change, temperature, precipitation, Central Asia

JEL classifications: Q15, Q18.

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Introduction

Climate change (CC) is no longer a theoretical or distant issue, as its widespread consequences are becoming increasingly clear around the world. Over the past century, the Earth's surface has experienced a temperature increase of 0.8 °C, with over 75% of this rise occurring in the past three decades (Hansen *et al.,* 2006). The resulting impacts include reduced agricultural productivity, declining crop yields, soil degradation, and erosion, all contributing to lower food security (FS). The concept of Vulnerability, Adaptation, and Resilience, outlined by the IPCC (2022), underscores that extreme weather events such as droughts, floods, and intense rainfall exacerbate the vulnerability of food systems, leading to food shortages, poverty, malnutrition, and volatile food prices. To mitigate these impacts, the food and agricultural sectors must adopt practices that build resilience and adapt to shifting climatic patterns. This includes the cultivation of climate-resilient crops, enhancement of soil health, efficient water management, and sustainable development strategies aimed at reducing susceptibility to climate stresses (IPCC, 2022).

The occurrence of extreme weather events, including high temperatures and severe droughts, poses an ongoing challenge to food security, threatening global nutrition and agricultural stability. Agriculture, inherently sensitive to climatic variability, faces increasing strain from changing precipitation patterns and higher temperatures, which in turn directly impact food availability and crop productivity (Godfray *et al.,* 2010). Experts have highlighted the harmful effects of CC on FS, predicting that by 2080, an estimated number ranging from 5 million to 170 million individuals worldwide could face intense food shortages (Schmidhuber and Tubiello, 2007). FS, particularly in its utilisation dimension, continues to be compromised by widespread malnutrition and micronutrient deficiencies. The Global Nutrition Report highlights that over 2 billion people suffer from at least one micronutrient deficiency, and 790 million people consume less than 2,100 calories per day. Moreover, 160 million children under the age of five are stunted, and 50 million are severely underweight. The degradation of a quarter of the Earth's land area, affecting 3.2 billion people, predominantly rural communities and smallholder farmers, exacerbates this global challenge (IFPRI, 2015). The research work presented here aims to draw attention to the localised implications of these global challenges, with Central Asia (CA) serving as a representative case study.

Currently, approximately five million individuals experience insufficient access to food sources who are residing in CA (Peyrouse, 2013). The region's agricultural sector faces significant threats from climate-induced challenges such as rising temperature, altered precipitation patterns, and fluctuations in river flows (Meyers *et al.,* 2012). Notably, the region's average surface air temperature has increased by 0.36 - 0.42°C for every ten years over the past 33 years (Hu *et al.,* 2014), while average precipitation has risen by 4.63mm per decade (Luo *et al.,* 2019). Heavy rainfall and storm-induced erosion further diminish the availability of arable land (Christmann *et al.,* 2009), while CC also impacts the prevalence and severity of pests and diseases, complicating agricultural management (Meyers *et al.,* 2012). Water scarcity is increasing, with competing demands from agriculture, industry, and domestic use adding to the strain (Hanjra and Qureshi, 2010). The increased frequency of extreme temperatures pushes crops closer to their thermal tolerance limits, undermining growth and yields (Lioubimtseva and Henebry, 2012). CA's heavy reliance on agriculture makes it particularly susceptible to CC's destabilising effects on food systems and regional economies.

While extensive research has been conducted globally on the influence of CC on the four pillars of FS – availability, access, utilisation, and stability – a significant gap persists in the literature focusing on CA. Most existing studies either address isolated aspects of FS or focus on regions such as Sub-Saharan Africa or South Asia, leaving the unique challenges of CA underexplored. The region's specific conditions, including acute water shortages, significant land degradation, and economic dependence on agriculture, necessitate a comprehensive and targeted analysis. Research is lacking on how CC – particularly temperature increases and precipitation variability – impacts all dimensions of FS in the region. This gap highlights the need for insights that can inform policy and foster strategies to bolster resilience and adapt to climate challenges.

This research aims to bridge this gap by assessing the multifaceted impacts of CC on FS in CA, with particular attention to temperature and precipitation changes. The study seeks to examine the implications for agricultural productivity, food access, and public health and to identify strategies that can enhance the resilience of food systems. Additionally, it aims to provide recommendations to secure food supply and improve the living standards of the region's population.

Literature Review

The issue of FS, encompassing whether there is enough food to feed the global population and the factors influencing this, has been the focal point of extensive research. Studies typically address key questions, such as: (i) Is global food production sufficient? (ii) Do people have adequate access and financial means to obtain food? (iii) Is food being utilised properly? (iv) Can sustainable food production be maintained in an environmentally friendly manner? The impact of CC has emerged as a critical element affecting these questions. A substantial body of research (El Bilali *et al.,* 2020; Kumar *et al.,* 2018; Muchuru and Nhamo, 2019) has underscored the significant consequences of CC on rural communities, where agriculture is pivotal.

The relationship between CC and FS has been studied at various levels – global, regional, national, and household (Maxwell, 1996; Pinstrup-Andersen, 2009). The findings, however, are inconsistent and often contingent on the analytical frameworks, methodologies, and data characteristics employed (Table 1).

Despite the breadth of existing studies, the findings on the impact of CC on FS are varied. While some research identifies significant negative consequences, others report minimal or context-specific effects. The debate continues, and further research is essential to reach a more comprehensive understanding.

The literature highlights that while many studies examine the influence of CC on specific dimensions of FS, integrated analyses encompassing all four pillars – availability, access, utilisation, and stability – are rare. Firdaus *et al.* (2019) highlight that while CC's impact on food availability has been well-documented, other dimensions such as access, utilisation, and stability are often overlooked. They advocate for future research to adopt a more holistic approach. In response to this gap, our research examines the comprehensive impact CC on all four pillars of FS in CA.

To illustrate the scope of existing research, we categorised studies into two main groups: (i) those that investigate the impact of CC on each dimension of FS separately, and (ii) those that address multiple or all dimensions simultaneously (Table 2). For example, many scholars have examined how climate change affects food availability (Abbas, 2022; Mekonnen *et al.,* 2021; Wu *et al.,* 2021; Fuller *et al.,* 2018; Zhao *et al.,* 2017). Similarly, the impact on food access has been reviewed by Asare-Nuamah (2021), Wang (2010), Alvi *et al.* (2021) and Wossen *et al.* (2019).

Climate Change and Food Availability

Research examining the link between CC and food availability indicates significant negative impacts. Zhao *et al.* (2017) demonstrated how global warming reduced the yields of staple crops such as maize, wheat, rice, and soybean.

Table 1: Reviewed studies on the FS - CC nexus at various levels.

FS Researchers Group			
Global level	**Regional level**	**National level**	**Household Level**
Zhao *et al.* (2017); Schmidhuber *et al.* (2007); Wheeler *et al.* (2013).	Singh *et al.* (2022); Mumuni *et al.* (2023); Lin *et al.* (2022); Fuller *et al.* (2018); Affoh *et al.* (2022); Alvi *et al.* (2021).	Mahapatra *et al.* (2021); Verschuur *et al.* (2021); Wu *et al.* (2021); Abbas (2022); Wang (2010); Wossen *et al.* (2019); Jibrillah et al (2018); Guo *et al.* (2023)	Mekonnen *et al.* (2021); Asare-Nuamah (2021).

Source: Own composition

Table 2: Categorisation of FS researchers.

First Group			
CC's Impact on Food Availability	**CC's Impact on Food Access**	**CC's Impact on Food Utilisation**	**CC's Impact on Food Stability**
Abbas (2022); Mekonnen *et al.* (2021); Wu *et al.* (2021).	Asare-Nuamah (2021); Wang (2010); lvi *et al.* (2021); Wossen *et al.* (2019).	Dietz (2020); Mahapatra *et al.* (2021).	Ribeiro *et al.* (2021); Jibrillah *et al.* (2018).
Second Group			
CC's Impact on Triple Pillars of FS		**CC's Impact on Quadruple Pillars of FS**	
Mumuni *et al.* (2023); Affoh *et al.* (2022).		Singh *et al.*, (2022)	

Source: Own composition

Fuller *et al.* (2018) found similar outcomes for banana yields in Central Africa, while Wu *et al.* (2021) showed that rising temperatures adversely affected maize production in China. In Pakistan Abbas (2022) highlighted that higher temperatures are expected to impede the long-term yields of major crops. Mekonnen *et al.* (2021) investigated Ethiopian household FS, noting that both rainfall and temperature significantly influenced crop productivity.

Climate Change and Food Access

CC also impacts food access. Alvi *et al.* (2021) employed an Integrated Assessment Model (IAM) to analyse FS in South Asia under climate scenarios, revealing rising food prices and diminished consumption. In Ghana, Asare-Nuamah (2021) noted that lower crop yields due to CC led to food insecurity as households struggled to afford sufficient food. Conversely, Wang (2010), using panel data from 1985 to 2007, found no significant impact of CC on food prices in China, demonstrating the variability in findings.

Climate Change and Food Utilisation

Dietz (2020) underscored the need for collaborative action to address the link between CC and nutritional outcomes. Mahapatra *et al.* (2021) found that in India, increased agricultural vulnerability due to CC correlated with poor nutrition among children, with significant percentages suffering from anaemia and malnutrition. Guo *et al.* (2023) used a copula approach to analyse food consumption in Nepal, demonstrating that even slight increases in climate risk reduced both calorie intake and dietary diversity.

Climate Change and Food Stability

Food stability is influenced by the other three pillars – availability, access, and utilisation (Stephens *et al.,* 2018). Ribeiro *et al.* (2021) developed a food stability model using expert insights and emphasised sustainable food production as a priority, especially with a growing population. In Nigeria, Jibrillah *et al.* (2018) reported that increasing temperatures and reduced rainfall over a decade led to significant vegetation loss, adversely impacting food stability and economic resilience.

Despite the extensive body of research, few studies comprehensively address all four dimensions of FS in a regional context. Manikas *et al.* (2023) noted that out of 78 publications in their systematic review, only three covered all four dimensions, none of which assessed the impact of climate indicators. Additionally, regional studies focusing on CA are scarce, with most research concentrating on areas like Sub-Saharan Africa or South Asia. Singh *et al.* (2022) conducted one such regional study for the South Asian AOR, but its scope and methods differ from our research.

This study aims to fill this gap by analysing how CC impacts the four pillars of FS in CA using regional panel data. The research will address the following questions:

- What climatic factors most significantly affect food production in CA, and how do temperature changes influence cropland areas and the food production indices?
- How do temperature changes in CA impact the stability of the food system, including the per capita food supply and average dietary energy requirement?
- Which climate variables contribute to the prevalence of anaemia among women of reproductive age due to temperature changes?
- What strategies can be developed to mitigate CC's negative effects on agriculture and public health in CA?

Theoretical/Conceptual Framework

Understanding the impact of CC on FS requires a comprehensive theoretical foundation that integrates both food security frameworks and vulnerability theory. This research draws upon two primary theoretical perspectives: (i) the FAO food security framework, which defines FS through its four key dimensions (availability, access, utilisation, and stability), and (ii) the IPCC vulnerability framework, which conceptualises vulnerability as the exposure, sensitivity, and adaptive capacity of a system to external stressors, such as CC as illustrated in Figure 1.

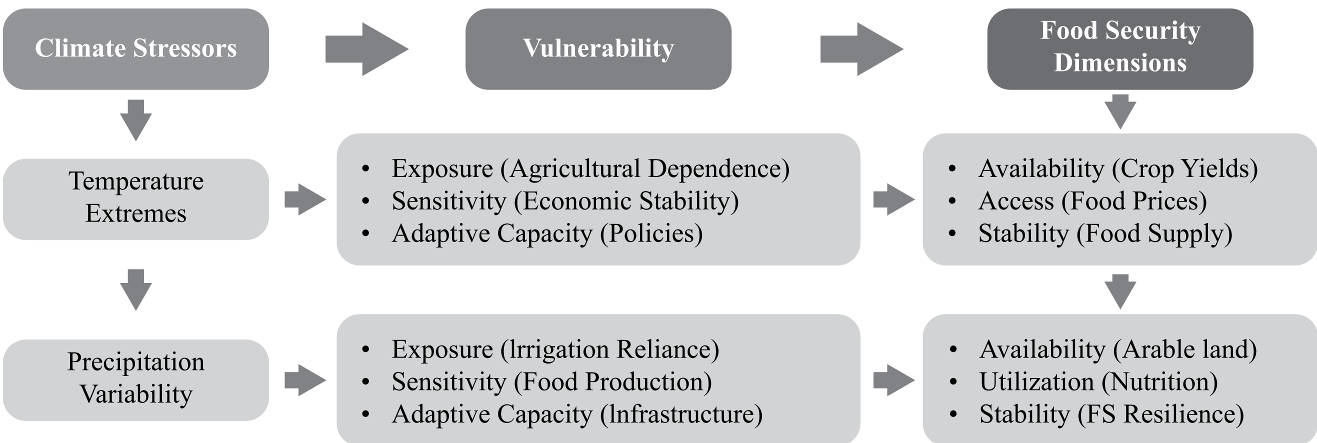

Figure 1: Conceptual Framework of the study.

Source: Authors' illustration

To make these frameworks more concrete, as well as to link them more directly to our empirical analysis, we identify some of the major theoretical components associated with key indicators of food security. For instance, food availability is associated with agricultural productivity, such as cereal yields, while food access is proxied by GDP per capita and undernourishment prevalence. While explaining in detail how vulnerability theory informs our understanding of how climate shocks exacerbate food insecurity through disruptions in the FS dimensions, we intend to provide an explanation of how each component of the vulnerability theory, namely exposure, sensitivity, and adaptive capacity, interacts with the dimensions of food security. Vulnerability theory helps explain how climate shocks aggravate food insecurity by the effect it produces on exposure, sensitivity, and adaptive capacity.

Extreme weather, such as floods and droughts, disrupts the production of agricultural produce, as a consequence reducing FS and availability. The sensitivity of the agriculture industry to climate-related factors means decreased crop yields and increased food prices due to rise in temperature and erratic rainfall, while lower access to food, and lower nutritional values impinge upon food utilisation to cause malnourishment. Adaptive capacity reflects how well a region can respond to these different challenges. Whereas solid infrastructure and economic stability in some countries can enable adaptation to the risks associated with climate change, in countries where poverty and weak governance prevail, the opposite occurs, exacerbating food insecurity across all its dimensions. Integrating these elements into the FAO food security framework helps in capturing how climate variability accentuates food insecurity by disrupting all four dimensions of food systems: availability, access, utilisation, and stability in CA. The integrated approach, therefore, permits an in-depth analysis of the socioeconomic and environmental drivers of food security in the region.

Materials and Methods

Data collection and variables

This study utilised a panel data analysis to assess the effects of CC on FS. The dataset spans 21 years (2000-2020) and includes countries within CA to capture temporal and regional variations in the data.

This study used four explanatory and three control variables: extreme hot temperature, extreme cold temperature, low rainfall, heavy rainfall, human development index, net migration, and political stability and absence of violence or terrorism. The indicators of FS used as dependent variables are GDP per capita (PPP), food production index, cereal yield, arable land, prevalence of undernourishment, per capita food supply variability, percent of arable land equipped for irrigation, average dietary energy supply adequacy, average dietary energy requirement, prevalence of anaemia among women of reproductive age and percentage of children under 5 stunted (see Table 3).

Table 3: Description of variables used.

	Variables	Unit	Symbol	Sources
Dependent	**Availability** Cereal yield	kg per hectare	Availability1	FAOSTAT
	Food production index (2014-2016=100)	index	Availability2	World Bank
	Arable land	%	Availability3	FAOSTAT
	Access Gross domestic product per capita, PPP	constant 2017 international $	Access1	FAOSTAT
	Prevalence of undernourishment (3-year average)	%	Access2	FAOSTAT
	Stability Percent of arable land equipped for irrigation (3-year average)	%	Stability1	FAOSTAT
	Value of food imports in total merchandise exports (3-year average)	%	Stability2	FAOSTAT
	Per capita food supply variability	kcal/cap/day	Stability3	FAOSTAT
	Utilisation Average dietary energy supply adequacy (3-year average)	%	Utilisation1	FAOSTAT
	Average dietary energy requirement	kcal/cap/day	Utilisation2	FAOSTAT
	Percentage of children under 5 years of age who are stunted (modelled estimates)	%	Utilisation3	FAOSTAT
	Prevalence of anaemia among women of reproductive age	15-49 years	Utilisation4	FAOSTAT
Independent	Annual minimum temperature	ºC	minT	WBCCKP
	Annual maximum temperature	ºC	maxT	WBCCKP
	Low rainfall	number of days	lowRainfall	NASA
	Heavy rainfall	number of days	heavyRainfall	NASA
Control	Human development index	index	HDI	WB
	Net migration	number of people	NM	WB
	Political stability and absence of violence/ terrorism	index	PS	WB

Source: Own composition

Data analysis

The fixed-effects regression model was used to analyse panel data and examine the impact of CC on FS indicators. This model is preferred over the random-effects model due to the presence of country-specific unobserved heterogeneity, which could otherwise bias the results. To formally justify the use of the fixed-effects model, we conducted a Hausman test, which compares the efficiency and consistency of fixed-effects and random-effects estimates. The results indicate that the fixed-effects model is more appropriate. The fixed-effects model was built following the methods of Otrachshenko *et al.* (2018) and Sun and Zhang (2021):

$$\begin{aligned} FS_{it} &= \beta_0 + \beta_1 minT_{it} + \beta_2 maxT_{it} + \\ &+ \beta_3 lowRainfall_{it} + \beta_4 heavyRainfall_{it} + \\ &+ \beta_5 HDI_{it} + \beta_6 NM_{it} + \beta_7 PS_{it} + \\ &+ \gamma_i + \mu_t + e_{it} \end{aligned} \quad (1)$$

where *i* and *t* indicate CA countries and time periods, accordingly. FS_{it} represents food security and its four dimensions: availability, access, stability, and utilisation. $MinT_{it}$ and $maxT_{it}$ are the group of temperature in country *i* during year *t*. $LowRainfall_{it}$ and $heavyRainfall_{it}$ are indicators of precipitation group in country *i* during year *t*, HDI - human development index, NM - net migration, PS - political stability and absence of violence or terrorism, country-specific fixed effects is γ_i, time-specific fixed effects is μ_t, and e_{it} is the random error term.

The temperature data used in this study was sourced from the Climate Change Knowledge Portal of the World Bank (CRU dataset), specifically focusing on temperature shocks and annual average minimum and maximum temperatures. Among these variables, the annual average mean temperature was excluded from the analysis, and the minimum and maximum temperature extremes were emphasised for their relevance in understanding climate dynamics. Temperature shocks are important as they directly influence agricultural productivity, crop yields, and the overall climate resilience of the region.

Precipitation data was collected on a daily basis from the POWER Project website, which is supported by NASA. The precipitation data was categorised into three bins based on the amount of rainfall: low rainfall (0-10 mm), normal rainfall (10-20 mm), and heavy rainfall (above 20 mm). Following the approach in Otrachshenko *et al.* (2017), the analysis specifically examines the impacts of low and heavy rainfall on FS, excluding the normal rainfall category as an intermediary state. This approach focuses on how extreme precipitation patterns (either too little or too much) affect food availability, access, utilisation, and stability, critical pillars in assessing FS.

This study covers multiple regions across CA, providing a comprehensive understanding of the region's diverse climatic conditions. The dataset includes:

- Kazakhstan: Temperature and precipitation data were collected from fourteen regions (oblasts), capturing regional variations across the country's vast expanse.
- Kyrgyzstan: Seven regions of Kyrgyzstan contribute detailed meteorological data to the study.
- Tajikistan: Four key regions in Tajikistan are part of the dataset, further enriching the geographic spread of the data.
- Turkmenistan: Data from five regions of Turkmenistan is included, contributing to the overall climatic analysis.
- Uzbekistan: Thirteen regions of Uzbekistan are involved, offering valuable insights into the climatic patterns in this key CA country.

This extensive geographical coverage ensures that the study incorporates a wide variety of climatic conditions, making the analysis of temperature and precipitation patterns across CA highly nuanced and robust.

The research methodology employs a comprehensive analytical model designed to evaluate the impacts of extreme temperature and precipitation shocks on FS across different regions of CA. This model uses extensive temperature and precipitation data collected from various regions to assess how fluctuations in these climatic variables affect the four pillars of FS.

The inclusion of regions with diverse climatic patterns enhances the reliability of the study's outcomes, ensuring that the findings are reflective of the broader climatic dynamics in CA. The focus on extreme temperature shocks and heavy or low precipitation ensures that the study captures the most disruptive climate events that are likely to exacerbate vulnerabilities in food systems.

By leveraging a rigorous model design and incorporating a wide geographical spread, this methodology enhances the robustness of the study's conclusions, offering a detailed exploration of how CC impacts FS in the region.

Results

The regression analysis, employing a fixed-effects model, reveals mostly a significant negative correlation between weather shocks and food security. By considering unobserved heterogeneity across countries, we enhance the reliability of our findings. The fixed effects help control for time-invariant factors that could otherwise confound the relationship between climate variables and FS, providing more reliable estimates of the impact of the temperature and rainfall on the various dimensions of FS. In CA, where climatic conditions have a major impact on the prosperity of the agricultural sector, even a slight change in temperature can have a significant impact on FS.

Surprisingly, the food production index can increase by a remarkable 15.76% with an annual minimum temperature increase of just one degree (see Table 4). This suggests that the colder months in the region are beneficial for crops. However, the situation is not as simple as it seems. The dynamics of the drought and the reduction in arable land highlight the vulnerability of the system. The drought reduces the area of arable land, which in turn limits the resources available for agriculture. The region loses 0.098% of its arable land for every additional day of drought. A decrease in temperature leads to an expansion of arable land equipped with irrigation systems. For every 1°C increase in annual minimum temperature in CA, the percentage of arable land equipped for irrigation increases by 0.139%. Conversely, for every 1°C increase in annual maximum temperature, the percentage of arable land equipped for irrigation decreases by 0.134%. This land is an essential resource to ensure the sustainability of the food system.

One of the most striking findings is that a 1°C increase in annual maximum temperature reduces per capita food supply variability by 22.060 kcal per person per day. Rising temperatures can disrupt the stability of the food system by increasing the energy required from food. A 1°C rise in annual maximum temperature reduces the average dietary energy requirement by 19.66 kcal per person per day. Temperature fluctuations are also linked to health problems. An increase of 1 degree C in annual maximum temperature leads to a 3.07 percent increase in the prevalence of anaemia among women of reproductive age. This illustrates the complex relationship between climate and health, and it is important to note that climate is not just weather, but a critical factor that affects quality of life.

The situation becomes more complex when global variables such as the Human Development Index are examined. While a prominent level of human development may appear to have a negative impact on crop yields, it promotes increased food production and improved quality of life. Political stability also plays a crucial role. A strong and stable government promotes agricultural development, whereas an unstable government may create significant social and economic problems.

CA, with its unique historical and geographical characteristics, serves as an important case study for analysing the relationship between climate factors and FS. The regression results reveal a complex mosaic in which CC, such as temperature increases or decreases and droughts, plays a key role in changing FS outcomes. This highlights the need for an integrated approach combining economic, social, and political measures to strengthen the region's food system. Using these analytical data and conclusions, it is possible to develop effective strategies and solutions aimed at ensuring the stability and well-being of everyone living in CA.

Table 4: Fixed effects analysis results.

Climate Variable	FS Dimension	Coefficient	P-value
minT	Availability2	15.766*	0.092
	Stability1	0.139**	0.049
	Utilisation4	-3.268**	0.038
maxT	Stability3	-22.060*	0.060
	Utilisation2	-19.663*	0.055
HDI	Availability1	-852.711**	0.032
NM	Availability1	0.008*	0.051
	Utilisation2	0.001***	0.006
PS	Availability2	19.651***	0.000
	Access2	-4.432***	0.007
	Stability2	0.120***	0.003
	Utilisation1	9.354***	0.000
	Utilisation2	5.523***	0.000
	Utilisation3	-3.736**	0.011

Note: *, **, *** means significant at 0.1, 0.05, 0.01 levels, respectively; *minT* – Annual minimum temperature, *maxT* – Annual maximum temperature, *lowRainfall* – Low rainfall, *heavyRainfall* – Heavy rainfall, *HDI* – Human Development Index, *NM* – Net migration, *PS* – Political stability and absence of violence/terrorism.
Source: Own calculations

Discussion

In our research, CC has had both negative and positive impacts on FS. According to our fixed-effects analysis, weather shocks mainly affected food availability, food stability, and food utilisation. These findings highlight the vulnerability of agricultural systems in CA to CC, with potential implications for crop yields and overall FS. Extreme temperatures and unstable rainfall patterns can disrupt agricultural production, lead to land degradation and malnutrition, and cause fluctuations in food availability, stability, and utilisation.

The result highlights both the positive and negative impacts of CC on food availability. Specifically, the fixed-effects analysis reveals that annual temperatures have a positive correlation with food production in CA. This contrasts with the broader global trend, where studies like Zhao *et al.* (2017) and Fuller *et al.* (2018) demonstrate the adverse effects of CC on key staple crops such as maize, wheat, rice, soybean, and banana. National-level studies, including Wu *et al.* (2021) and Abbas (2022) also underscore the vulnerability of local agricultural production to changing weather patterns. These differences between our findings and the findings of other studies can be explained by regional agro-climatic characteristics in CA. For instance, unlike tropical and temperate regions, CA's agricultural systems are highly constrained by cold temperatures, especially in early spring and late autumn. Moreover, a rise in minimum temperatures reduces frost frequency, extends the growing season, and improves conditions for winter crops such as wheat and barley. Further, the results of the research are consistent with the findings of Mekonnen *et al.* (2021), our analysis indicates that precipitation, especially excessive rainfall, negatively impacts food availability, leading to a reduction in arable land in the region. Extreme weather events such as floods and droughts further compound this vulnerability, undermining crop yields and overall agricultural productivity.

The impact of CC on food access in CA appears to be less pronounced according to our analysis. Panel data analysis suggests no significant effect of climate shocks on food access, which aligns with Wang (2010) study, which found that weather shocks had minimal influence on consumer prices. Despite this, our findings also confirm that CC negatively affects agricultural output, as noted by Asare-Nuamah (2021), leading to food insecurity for many households. In particular, those with limited resources struggle to afford sufficient food, thereby exacerbating food insecurity. Climate-induced disruptions in food production can limit the availability of affordable food, forcing households to rely on adaptive strategies that may not fully mitigate the adverse effects of these climatic shifts.

Food utilisation, particularly nutritional intake, is significantly impacted by CC. Our analysis shows that extreme temperatures have a harmful effect on dietary intake, with particular implications for productive-age women. This is consistent with research by Dietz (2020), who highlighted a strong link between CC and FS in CA. For instance, a 1°C increase in annual maximum temperature leads to a 3.07 percent increase in the prevalence of anaemia among women of reproductive age. This relationship suggests multiple pathways through which CC exacerbates malnutrition and micronutrient deficiencies. Firstly, temperature-induced crop yields decline and dietary changes, where rising temperatures reduce yields of iron-rich staple crops, such as wheat, maize, and legumes. Moreover, as Schmidhuber and Tubiello (2007) emphasize that heat stress reduces the nutritional quality of crops, leading to lower iron concentrations in staple foods. Secondly, micronutrient deficiencies increase incidences of food-borne and vector-borne diseases. As Dietz (2020) indicates, heat stress increases bacterial contamination of food, leading to gastrointestinal infections that impair iron absorption.

These changes in climate patterns disrupt food consumption patterns and nutritional outcomes, underscoring the need for policies aimed at improving the nutritional status of vulnerable populations. This finding further underscores the complexity of CC's impact on FS, which extends beyond mere availability to the very quality of the food consumed.

Our findings also align with studies such as those by Stephens *et al.* (2018) and Jibrillah *et al.* (2018), emphasising the role of CC in destabilising food supply systems in CA. The stability of FS is deeply interconnected with food availability, access, and utilization. Our analysis shows that a 1°C increase in annual maximum temperature decreases the percentage of irrigated arable land by 0.134%, indicating a negative impact of heat stress on water resource management. These phenomena can be explained by increased evapotranspiration and the necessity for water. This means that higher temperatures accelerate evapotranspiration, reducing surface water availability for irrigation. This effect is particularly severe in CA, where 80% of irrigated agriculture depends on river-fed irrigation, which is highly sensitive to climate fluctuations (Christmann *et al.,* 2009). Moreover, rising temperatures affect glacier retreats in the Tien Shan and Pamir mountains, which serve as water sources for irrigation systems in Kazakhstan, Kyrgyzstan, and Uzbekistan. Luo *et al.* (2019) emphasised that reduced glacial input has already contributed to declining water availability in major rivers like Amu Darya and Syr Darya.

These reductions in food availability and the ability to utilise water resources for agriculture contribute to diminished food stability, which in turn affects the resilience of households to food insecurity. Furthermore, as pointed out by Sirba and Chimdessa (2021) and Jibrillah *et al.* (2018), factors such as high temperatures and low precipitation have severely impacted food stability, particularly in regions with limited adaptive capacity. The reduction in crop yields, cereal production, and livestock output, exacerbated by changing weather patterns, threatens not only nutrition but also household income, further straining FS in the region.

Policy recommendations

Modern agriculture in CA countries faces complex challenges, including climate variability, resource constraints, and institutional limitations. Adapting to these challenges requires a strategic approach that balances technological innovation, policy support, and capacity building while considering CA's economic and governance realities.

Optimising irrigation systems is one of the key priorities, given CA's heavy reliance on glacier-fed seasonal water sources. However, widespread adoption of modern irrigation is often hindered by limited financial resources, outdated infrastructure, and governance inefficiencies. To address this, CA countries should establish regional cooperation on transboundary water management to improve water allocation efficiency. Moreover, Public-private partnerships can be set up to attract foreign investment in drip and precision irrigation.

Beyond these technological solutions, a more comprehensive strategic approach is needed to make the transition to sustainable agriculture. Priority should be given to environmentally friendly practices such as multi-layer farming, water-saving technologies, and the use of sustainable crop varieties. Such practices will not only reduce pressure on ecosystems. They will also improve soil quality, making crops more resilient to climate change.

Education has a key role to play in the adaptation of the agricultural sector to the new realities. An integral part of sustainable development is the expansion of training programmes for farmers and agricultural professionals, with a focus on adaptation to CC and the introduction of new agricultural technologies.

A crucial role is also played by research funding. The necessary tools to adapt to changing conditions can be provided by supporting basic and applied research to develop innovative technologies and hybrid plant varieties. However, sustainable development is not possible without the creation of the conditions for political and economic stability. This will provide a sound basis for the agricultural sector to invest, innovate, and develop over the long term.

Finally, a key role in maintaining public health and agricultural sustainability will be played by specific public health programmes to prevent the spread of climate-related diseases. To conclude, modern agriculture faces many challenges in Central Asia, but there are also many solutions that can help it develop sustainably. Through a comprehensive approach that includes innovating, educating, and supporting, agriculture can thrive in an era of climate change.

Conclusions

Climate change presents a significant challenge to agriculture and food security in Central Asia, due to its semi-arid continental climate, reliance on irrigation, and unique economic structures. This study examined how temperature extremes and precipitation changes impact the four pillars of FS, offering key insights into climate-related risks and adaptation needs.

The findings show that temperature extremes have mixed effects on food production. Rising minimum temperatures improve yields by reducing cold stress and extending growing seasons, while higher maximum temperatures reduce arable land due to water shortages and soil degradation. Precipitation variability poses a major risk to food stability, as both low and excessive rainfall disrupt crops and strain water resources.

While these results provide valuable insights for CA, they cannot be applied universally. The region's climate and agricultural systems differ from those in tropical or coastal areas, but the findings may still be relevant to other semi-arid, water-scarce regions such as Mongolia, Western China, and parts of the Middle East.

However, some limitations must be acknowledged. This research relies on country-level data for CA, which may hide subnational differences in food security. For instance, rural and urban areas or irrigated and non-irrigated regions within a single country may experience climate impacts differently, but these variations are not fully captured. Additionally, while the fixed-effects model controls for country-specific differences, it does not explicitly account for short-term shocks, such as economic crises, pandemics, or sudden policy changes, that may have temporarily influenced FS trends.

Beyond environmental, socio-economic, and political factors, other important determinants such as technological advancements, cultural influences, and biological factors were not included in this study but should be explored in future research. Another challenge was the availability of accurate, complete, and up-to-date data for certain countries and variables. Data limitations can affect the robustness of findings, highlighting the need for more comprehensive and reliable datasets. Addressing these data gaps in future studies will further enhance the understanding of climate and food security dynamics in CA.

These findings highlight the need for targeted adaptation strategies, including improving irrigation efficiency, diversifying crops, and strengthening policies to reduce climate risks. Future research should explore local variations, long-term adaptation efforts, and cross-regional comparisons to support more effective climate resilience planning.

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Trade and sustainability: analysing Specific Trade Concerns (STCs) through the Theory of Change

This study explores the link between trade and sustainability, focusing on Sanitary and Phytosanitary (SPS) measures within the WTO framework. It highlights the importance of Specific Trade Concerns (STCs) as a dispute management tool and their implications for sustainability. Analysing three case studies – EU-China (African Swine Fever), EU-India (Methyl Bromide fumigation), and Senegal-EU (mango exports) – the paper identifies divergent, negotiable trade-offs, and cooperative behaviours among trading partners. The study applies the Theory of Change (ToC) framework to the three STCs to assess the effectiveness of linking trade with sustainability goals. Findings reveal that sustainability considerations are critical for resolving STCs and achieving policy coherence and integration. The EU-Senegal case demonstrates ToC alignment, showcasing the success of a cooperative approach in addressing sustainability. In contrast, unsolved issues in the EU-China and EU-India cases highlight faults in sustainability integration. The study underlines STCs' potential for modernising the WTO by fostering the linkages between trade and sustainability through institutional change.

Keywords: Specific trade concern (STC), Theory of Change (ToC), WTO, sustainability, European Union, China, Senegal, India

JEL classifications: F13, F18, Q17.

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Introduction

The role of trade in reducing poverty and integrating developing countries in the global world is widely recognised (World Bank Group and World Trade Organization, 2015 and 2018). International trade and investment have been shown to be essential to fighting poverty and achieving the Sustainable Development Goals (SDGs) of the United Nations (UN) Agenda 2030. Despite recognising the benefits of liberalisation through reducing tariff barriers, trade has faced growing protectionism in recent years (Gunnella and Quaglietti, 2019; Mariotti, 2023; Zahoor *et al*., 2023). The World Trade Organization (WTO), the main engine of this liberalisation, is under fire due to growing geopolitical tensions and the recognition that global competition has resulted in an unfair distribution of the economic gains and losses from trade experienced by sectors, regions and workers around the world (Stanford, 2020; Dullien, 2018). The WTO is experiencing a crisis of legitimacy and needs to be prepared effectively to address the challenges of rapid economic, political, social, technological and environmental change (Oonagh, 2020).

Discourses on the modernisation of the WTO refer to its three pillars: trade negotiations, trade policy monitoring and reform of the dispute settlement system (Mildner *et al.*, 2022; Van der Loo, 2022). Increasing attention is also paid to promoting environmental and social sustainability through trade. Agenda 2030 recognises international trade as a means to achieve socio-economic development; however, understanding the linkages between trade policy and sustainable development remains challenging for policymakers (UNCTAD, 2015 and 2016).

In recent years, the growing liberalisation of agricultural trade brought about by tariff reductions has been accompanied by an increasing use of non-tariff measures (NTMs) (Olper, 2017; Beguin, 2022; Grant and Arita, 2017; Matthews *et al*., 2017; Disdier and Fugazza, 2019; Beverelli *et al*., 2014). These are defined as measures other than the imposition of tariffs that have the potential to affect trade in terms of the quantity of goods traded, prices or both (DITC, UNCTAD, 2010). NTMs range from measures used as trade policy instruments with a mainly protectionist scope (the so-called non-technical measures) to technical measures with non-trade policy objectives aiming to protect health or the environment (UNCTAD, 2016). UNCTAD developed a comprehensive classification of NTMs in 2012, and it has been progressively updated to reflect the evolution of international trade (UNCTAD, 2019).

Most NTMs are represented by Sanitary and Phyto-Sanitary (SPS) measures and Technical Barriers to Trade (TBT) regulations. Although the latter predominates in total trade in terms of the number of products covered and as a share of trade value covered, the former dominates in agri-food trade (Disdier and Fugazza, 2019; WTO ITC UNCTAD, 2021). Approximately 80% of world agricultural trade is estimated to be affected by SPS measures, representing 10% of total world trade (UNCTAD, 2016).

Within the WTO, the SPS Agreement covers regulations on food safety and animal and plant health standards. SPS measures are primarily used to protect human health, animal or plant life and the environment, and thus directly address issues related to sustainable development. This increases friction between countries over SPS measures because of their potential to distort international trade (Roberts and Unnevehr, 2003). In turn, by affecting trade, they also indirectly impact sustainability through trade (UNCTAD, 2015 and 2016). Therefore, we can observe a reciprocal relationship between trade and sustainability, where one influences the other.

Under the SPS Committee, a peer review system exists to allow countries to learn more about each other's national implementation of SPS measures when they are considered adversely affecting trade in light of international obligations (Posada *et al*., 2022; Hoekman *et al.*, 2023). This system, called Specific Trade Concerns (STC), is considered a transparent monitoring tool to avoid trade disputes. STCs are raised orally in the SPS Committee, and progress made through bilateral discussions between trading partners is summarised in notes by the Secretariat. They are not formal disputes but are often a signal that a national measure taken by another WTO member is considered inconsistent with international rules (Horn *et al*., 2013). According to the literature, STCs have defused potential trade conflicts by resolving trade concerns non-litigiously (Horn *et al*., 2013; Posada *et al*., 2022; Holzer, 2019; Wolfe, 2020), leading some scholars to suggest using STCs to resolve trade frictions regarding national security issues in an expanded sense (Hoekman *et al.*, 2023). The literature also highlights the need to strengthen STCs to enable full participation of all WTO members, especially the less developed ones with more limited administrative capacity, information or financial resources for proactive and constructive engagement (Wolfe, 2020).

As STCs are raised because SPS measures are perceived to be overly trade-restrictive, thus affecting the achievement of sustainability goals, we analyse three STCs with the EU as a trading partner to identify potential problems that standards and their implementation pose for trade with a view on sustainability issues: a) EU-China on African Swine Fever (ASF), b) EU-India on Phytosanitary import restrictions, and c) Senegal-EU on the Rapid Alert System for mango imports.

An extensive literature has analysed STCs as a good proxy for non-tariff measures that constitute trade barriers (Laget and Deuss, 2023; Orefice, 2016; Fontagné *et al*., 2015), but to the best of our knowledge, no study has explored the sustainability issues behind STCs and the different perception of such matters of trading partners.

This study is developed within the TRADE4SD horizon project, and it aims to fill this gap through the three case studies, which are representative of the various behavioural dynamics of the EU and its partners in terms of reciprocity and asymmetries between countries regarding sustainability goals.

Moreover, we try to add new evidence to Wolfe's (2020) work on using STCs to manage conflicts within the WTO. In this context, we consider the Theory of Change (ToC) as a valuable tool to improve this system and contribute to resolving international frictions (Vogel, 2012), keeping in mind the goal of fostering positive linkages between trade and sustainable development. Institutions can contribute to building a bridge between trade and SDGs, ensuring that each component of the global value chain is actively involved in this integration process. Institutional building can be pursued mainly through two paths: policy coherence and policy integration (Cejudo and Michel, 2017).

The ToC represents an effective instrument for assessing policy coherence among different institutional levels, contributing to constructing links between trade and sustainability, and cooperating rather than competing in pursuing common goals. At the same time, given the established goals, the ToC contributes to assessing policy integration among measures and interventions in different fields (agriculture, trade, labour, safety standards, ecoservices, etc.). Institutional building is necessary to solve international controversies, and it is an incremental endogenous process requiring the involvement of all the actors interested in it (Pain, 2022).

Given the general framework of the ToC, we assess the extent to which this has been followed in the context of the three cases we chose to examine as well as whether there is a link between the stage the three cases are in and the proper setting of the ToC. It must be kept in mind, in fact, that the ToC is not a structured methodology but rather a process that needs to be built taking into consideration some relevant steps and interaction with the specific environment.

Our main objective is to analyse our case studies by applying the main steps of the ToC with the ultimate aim of verifying whether the ToC makes STCs more efficient and can be used as a conflict smoothing tool in the WTO. Our analysis demonstrates the validity of the ToC in bringing out sustainability issues underlying STCs, avoiding deadlock and contributing to the resolution of frictions more easily and quickly. In this sense the results of the analysis are generalisable, and the process can be applied to other cases, confirming the validity of the ToC applied to STCs.

This different reading of STCs through the lens of the ToC represents an example of WTO modernisation and a contribution to institutional change (Pain, 2022). In synthesis, the aim of this study is twofold:

1. To investigate how SPS measures may enhance the achievement of sustainability issues, as perceived by trading partners;
2. To outline a way to modernise the WTO in relation to sustainability through STC, with a view to increasing the participation of less developed countries following the principles of the ToC.

In the following pages, we first highlight the growing importance of STCs and their role in defusing potential disputes. In section 3, three case studies highlight the different sustainability issues underlying the STCs, as perceived by the trading partners. Section 4 focuses on a possible pathway for modernising the WTO, suggesting that STCs may be used to manage conflicts in alignment with a general ToC framework. Section 5 discusses the extent to which the results of our case studies are consistent with the different steps of a ToC, with a particular focus on sustainable issues. The final section concludes. Appendix A attempts to apply the ToC to our case studies dealing with trade and sustainable issues.

The relevance of STCs in WTO

The economic effects of standards NTMs have been thoroughly discussed (Josling *et al.,* 2004; Bureau *et al.,* 1998; Tian, 2003; Disdier and van Tongeren, 2010). TBTs, SPS and other "technical" NTM policies impacting the quality of products, or the way in which commodities are manufactured and sold to end users are examples of NTMs that resemble standards. Unlike tariffs, their effect on trade is more nuanced. The rationale is that, in comparison to tariffs, NTMs are more varied and complex. NTMs fall into sixteen categories, ranging from trade-related non-technical measures (like subsidies, quotas, anti-dumping, pre-shipment inspections, etc.) to product-related technical measures (like technical requirements and conformity evaluations). In 1995, both NTMs were implemented following the Uruguay Round agreements. The SPS and TBT agreements aim to safeguard consumers and the environment, thwart protectionism, aid in industry standardisation, and establish technical limits for particular items. TBTs and SPSs are frequently applicable to a product in one or more industries simultaneously. As such, it occasionally affects an entire industry. It can help trade by bringing better information and fostering greater trust between partners, or it can harm trade by adding to the administrative load and raising compliance costs for both exporters and domestic businesses through new rules about the environment and industrial processes. For other WTO members to provide feedback in either scenario, an SPS or TBT must be informed at the WTO as soon as possible. Changes may be made following the comment period. After that, the NTM is approved and released, taking effect at least half a year later. The new TBT or SPS is only in effect during this enforcement period, despite the possibility of some consequences resulting from anticipations.

Researchers have demonstrated a strong interest in product-related SPSs and TBTs since they address the majority of NTMs. WTO committees and councils are key fora where members raise trade concerns concerning measures that may affect trade. Since 1995, the use and discussion of trade issues increased and sometimes facilitated the resolution of trade issues between members. The database detailing trade problems makes it possible to classify them into different categories: a) Council for Trade in Goods (CTG), b) Market Access Committee (CMA), c) Committee for Import Licences (IL), d) SPS and TBT Committees. The graph below shows the current data from which TBT and SPS emerge as the main concerns raised.

As Figure 1 displays, there are currently roughly less than 90,000 notifications between TBT and SPS. 35,246 are the SPS notified compared to about 54,700 TBT measures for the period 1995-august 2024 (see WTO website for detailed information).

The impacts of SPSs and TBTs on trade are challenging to determine. In a study on the TBT and SPS regulations in the agri-food sector, Santeramo and Lamonaca (2019) provide insights into why there are diverse results in the literature. Different industries have distinct objectives for implementing TBTs and SPSs, leading to varying effects. To avoid diluting the significance of TBTs that are not restrictive, some research in the NTM literature has focused on STCs.

Trade concerns related to specific issues, such as SPS measures or TBT, can be raised at the WTO at any time from the notification until after the measures are in effect. These complaints are known as SPS STCs and TBT STCs. According to the official data from the WTO, 835 TBT STCs and 585 SPS were raised between 1995 and 2024. In the STC literature, it is assumed that a concern is raised because a TBT or SPS measure is restricting trade, and STCs are indicators of the most restrictive measures (Beghin *et al.*, 2015; Disdier *et al.*, 2023; Fontagné and Orefice, 2018; Fontagné *et al.*, 2015; Kamal and Zaki, 2018; Orefice, 2016).

Once an STC has been lodged, it can be brought up again at subsequent meetings either by the same countries who raised it initially or by new ones joining the discussion. The dates of the complaints are meticulously recorded: the “first raised date” signifies the initial instance when a specific concern was raised against a particular TBT or SPS measures issue. In contrast, the “last raised date” indicates the most recent recorded instance at the WTO. It is worth noting that multiple raised dates may exist within this period. A concern is considered resolved when no new raised dates have been raised for at least two years.

Food safety and animal health cover 66% of the measures subject to STCs, while plant health is less than 1/4 of the STCs (Figure 2 – STCs by objectives).

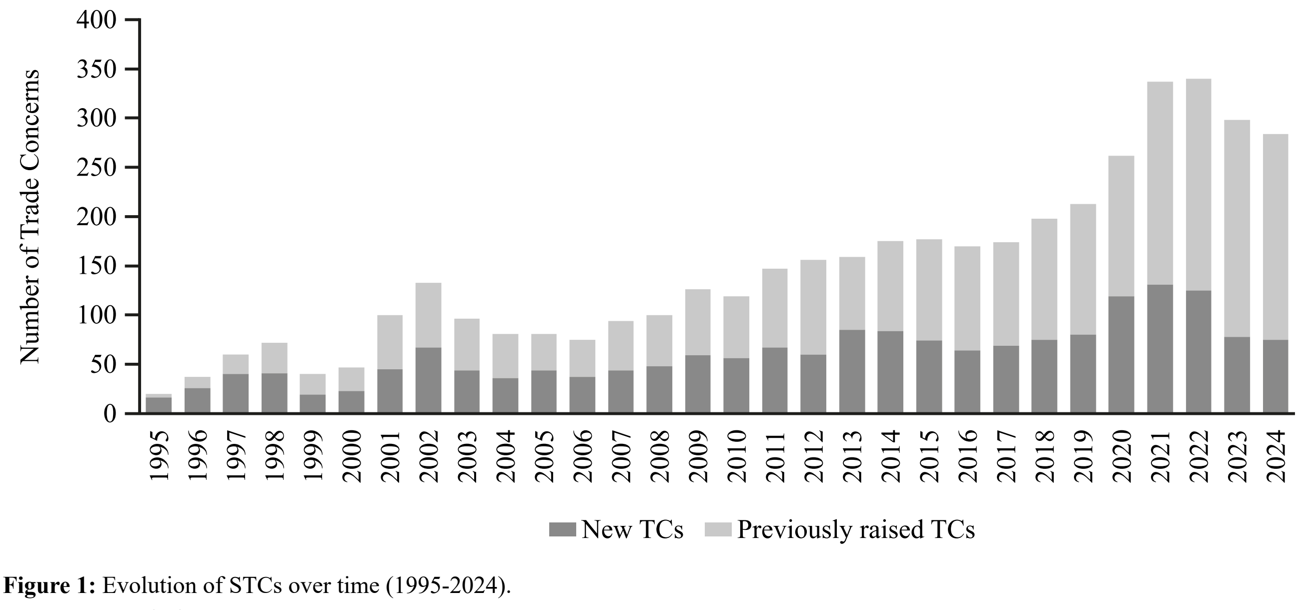

Figure 1: Evolution of STCs over time (1995-2024).

Source: WTO TCs database

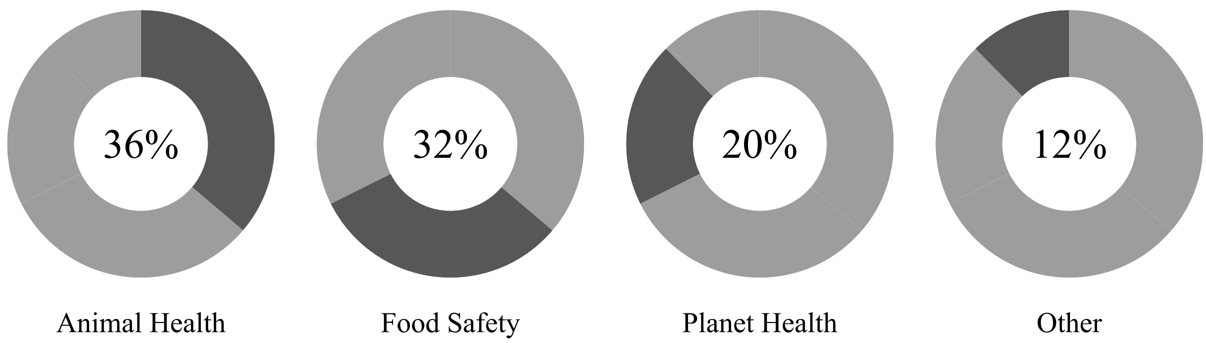

Figure 2: STCs by objectives.
Source: Authors’ computation is based on the WTO TCs database

The chapters with the most STCs raised are Chapter 02 - Meat and Edible Meat Offal, which has 189 STCs raised, followed by Chapter 22 - Beverages, spirits, and Vinegar, which has 133 STCs raised. Chapter 08 - Edible fruit and nuts; peel of citrus fruit or melons has 122 STCs raised, and Chapter 04 - Dairy produce; birds’ eggs; natural honey; edible products of animal origin, not elsewhere specified or included has 104 STCs raised.

As we review the notifications and their respective statuses, data analysis indicates that most trade concerns still need to be reported as resolved (82%). This high percentage suggests that many issues must be reported for resolution or updates. Only a tiny fraction is fully solved (13%), indicating that resolution rates might be low or that specific trade concerns take time to address. Even a smaller portion is discussed partially (5%), implying that while some progress has been made, these issues still need to be resolved entirely. This distribution may highlight challenges in the resolution process or a need for better tracking and reporting of these concerns.

The disputes over SPS and TBT measures stem from many reasons, extending beyond protectionist motivations and reflecting cultural disparities. These disputes encompass a wide range of concerns, including issues surrounding the labelling of genetically modified organism (GMO)-free products and other related matters. When we examine the STCs categories using keywords, the analysis emphasises that the primary areas of concern are those associated with human health and food safety.

When analysing keywords, “Human Health” (HH) appears most frequently (19.10%) and “Food Safety” (FS -19.34%) in the STCs, together accounting for over a third of the total (38.44% cumulative). This indicates that these topics are particularly significant and represent the primary specific trade concerns analysed and discussed in the three case studies presented in this article, as shown in Table 1 in the following section. Other significant keywords include Pesticides (6.89%), AH (7.32%), PH (7.20%), and MRLs (6.35%). These keywords collectively cover over 66% of the total entries by the cumulative percentage, highlighting their importance within the data. Less frequent keywords with lower individual frequencies but notable in specific contexts include “Zoonos” (2.47%), “Food Ad” (2.31%), and “Regionalization” (2.32%), contributing to a cumulative total of around 86%.

Finally, comparing the involvement of developed and developing members in raising STCs and the responses from the respective countries indicate that developed members tend to raise STCs more often for developing members or emerging markets. The United States is the most active member, raising 680 concerns, followed closely by the EU with 668 concerns and Canada with 335 concerns. Other notable members raising concerns include China (279), Japan (260), and Australia (222). The EU is the leading respondent, addressing 369 concerns raised by other members.

The United States also frequently responds to concerns, with 172 responses. Other significant respondents include China (157), India (132), Indonesia, the Republic of Korea, and the Russian Federation, each with 63 responses. The analysis of the data reveals some interesting interactions. Brazil and Mexico appear to be active raisers and respondents within the Americas, indicating an engaged dialogue within the region. Asian countries, such as Japan, China, and the Republic of Korea, also show significant activity, often responding to concerns from neighbouring or global counterparts.

The United States has raised numerous concerns (680 in total), with China as one of the primary respondents (157 responses). This reflects frequent interactions where the United States addresses trade issues that may involve China, highlighting common areas of concern like intellectual property, market access, and regulatory standards. Interesting is the case between the EU member states and India (the EU raising 668 concerns, often receives responses from India - 132 responses); this interaction might represent discussions on trade barriers, such as tariffs, sanitary and phytosanitary standards, and compliance with regulatory norms. Another interesting interaction emerges between Brazil, with 208 concerns raised and 172 responses from the United States. This two-way engagement may indicate mutual trade interests, often around agricultural exports, tariffs, and technical standards, where an emerging country like Brazil frequently interacts with a developed trade partner like the United States. These interactions suggest a dynamic relationship between developed, emerging and developing countries in resolving specific trade concerns, often revolving around regulatory standards, market access, and product-specific regulations. Developed countries frequently raise concerns about market entry, compliance, and safety standards in developing markets, while developing countries address regulatory barriers and trade restrictions in developed markets.

The perception of sustainability behind STCs

In recent decades, the increasing liberalisation of trade and the concurrent interest in promoting sustainability through trade have led to a growing number of NTMs, mostly related to product and process standards. These include SPSs and TBTs, both of which aim to prevent the creation of undesirable barriers to trade. Although most NTMs are non-trade related, changing market access conditions can indirectly impact trade. The direction and magnitude of such effects on trade and welfare are controversial, depending on the type of NTM, the countries/products/standards involved, and the methodology applied (Santeramo and Lamonaca, 2019; Beghin *et al.*, 2012; Roberts and Unnevehr, 2003; Curzi *et al.*, 2020).

The SPS Agreement allows WTO members to "provide the level of health protection they deem appropriate" while ensuring that this does not lead to overly restrictive trade measures. According to Miljkovic (2005), "selecting the appropriate level of protection is an act of sovereignty". Members are encouraged to use international standards but may adopt higher levels of protection if they are based on scientific justification and applied in a transparent and non-discriminatory manner.

The international standards, guidelines, and recommendations referred to in the SPS Agreement are developed by three other international organisations (the so-called "Three sisters"), which have gained importance following their involvement in the SPS Agreement (Roberts and Unnevehr, 2003). The three organisations are:

- the Codex Alimentarius Commission,
- the World Organisation for Animal Health (WOAH),
- the International Plant Protection Convention (IPPC).

The SPS Agreement is based on transparency obligations requiring Member countries to provide all information on the SPS measures they intend to introduce or modify. The system can be described as an inverted pyramid, with a significant number of notifications of SPS measures introduced or designed to be modified at the top and the actual number of disputes at the bottom (Figure 3). This system provides for an ongoing process of consultation between the parties after the notification, which is recognised as an essential step in limiting friction between countries (Posada *et al.*, 2022; Wolfe, 2020). As can be seen, only a limited number of notifications result in STCs, and an even smaller number result in actual trade disputes.

The three STCs analysed differ in many respects: the EU's position in the STC and on trade, the international organisations involved in SPS, the sustainability issues involved, the global dimension of the STC, the number of times the STC was raised, and its status (Table 1).

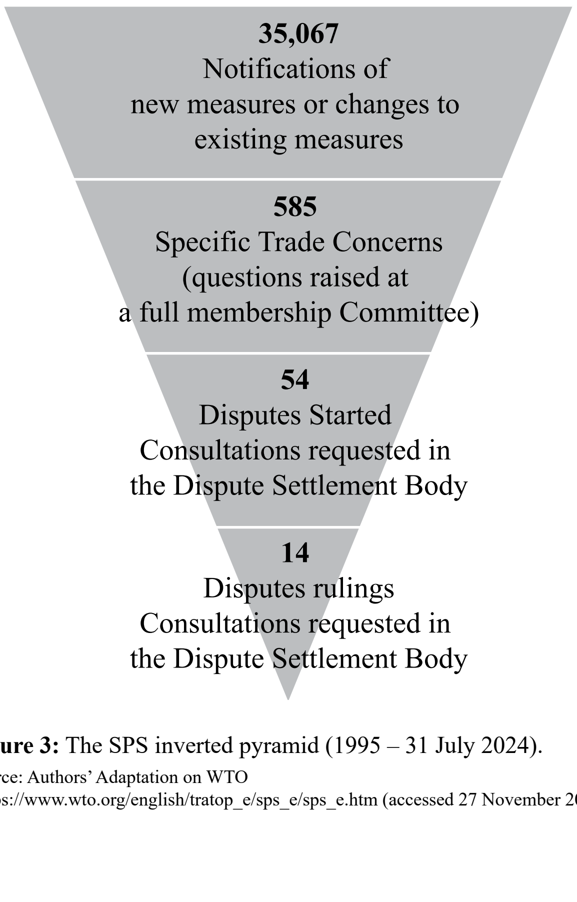

Figure 3: The SPS inverted pyramid (1995 – 31 July 2024).

Source: Authors' Adaptation on WTO (https://www.wto.org/english/tratop_e/sps_e/sps_e.htm (accessed 27 November 2024)

Table 1: Case studies on STCs.

Case studies	EU-China on ASF (STC m. 392)	EU-India on Fumigation with MBr (STC n. 186)	Senegal-EU on Mango (STC n. 272)
EU position in STC	Raising	Raising with USA Supported by Canada, Chile, New Zealand	Respondent
Number of times STC was raised (until February 2024)	19 (since July 2015)	3 (since March 2004)	1 (June 2008)
International organisations involved in SPS	World Organisation for Animal Health - WOAH	International Plant Protection Convention - IPPC	International Plant Protection Convention - IPPC
Primary subject keyword in STC document	Animal Health	Plant Health	Food safety
Other Keywords (from literature)	Food security	Climate change Food security	Food security
EU position in trade	Exporter	Exporter	Importer
Risk perception on sustainability issues	**China**: Defensive approach for economic and social effects on its territory **EU**: economic concerns in defence of its pork industry	**India**: Trade-off between sustainability objectives (food security vs climate change) **EU**: the effects of MBr on climate change	**EU-Senegal**: Cooperative approach between the two trading partners on economic, social and environmental concerns
The global dimension of STC	Yes	Yes	No
Status of STC	Still unsolved	Solved concerning procedural issues (only with the EU)	Solved

Source: Authors' elaboration

The EU-China case

The first STC deals with Chinese import restrictions from the EU due to ASF. As no vaccine is currently available, prevention is the better way to avoid introducing infected material into ASF-free countries through appropriate import policies and biosecurity measures. To ensure traceability, the measures taken should ensure the identification of animals and products derived, the traceability of the movements, the biosecurity measures in place and surveillance. The EU first raised the STC in July 2015 and has done it 18 more times, most recently in November 2023. China has imposed a country-wide ban on imports of pigs and pig products from EU Member States (MS) where ASF has been detected and does not recognise the EU regionalisation applied by the international standards set by the WOAH. The EU raised concerns about China's ban, considering it overly trade restrictive and inconsistent with China's obligations under the SPS Agreement and WOAH standards (regionalisation). On the other hand, China believes the ban is necessary because of the ineffective control of the disease by the EU MSs with different levels of prevention and control imposed following the SPS Agreement. Regionalisation allows a country to limit the spread of the disease to a restricted area while allowing trade to continue in the rest of the territory. The key element of the approach is the clear epidemiological separation of the animals and herds or flocks belonging to sub-populations of zones from other animals and all factors presenting a risk. Only a few countries partially or fully recognise the EU regionalisation measures for ASF. In contrast, many countries do not recognise the EU regionalisation measures at all. However, the range of products affected by the ban on imports from the EU is very broad and varies from country to country[1]. ASF is a highly contagious infectious disease affecting domestic and wild animals of all breeds and ages. Its spread worldwide has become a primary global source of crisis for the pork industry, with a high socio-economic impact on the affected countries due to restrictions on meat exports and limitations on local forest activities (Sánchez-Cordón *et al.*, 2018). Furthermore, its proliferation poses a severe problem for global food security, as pork meat is one of the primary animal protein sources and is expected to account for 34% of all the protein from meat sources by 2030 (OECD/FAO, 2021). China is both the largest producer and consumer of pig meat in the world, accounting for over 40% of the total in 2021.

The EU-China case study highlights the different perceptions of risk associated with food safety and food security between the two trading partners. The perceived failure to accommodate legitimate differences in food regulations is a crucial element that can increase resistance to trade liberalisation and lead to unanticipated policy decisions (Roberts and Unnevehr, 2003). China and the EU take divergent positions on regionalisation's impact, an issue widely discussed in the WTO. According to the EU Commission, under the umbrella of the Animal Health Law legal framework, which provides for strict measures to apply regionalisation based on scientific evidence, entirely in line with international standards and based on risk mitigation measures in areas affected by animal disease, the Special ASF control rules have proved to be effective in preventing/controlling/slowing down the spread of diseases, while allowing safe trade to continue without lowering the safety level of traded/exported commodities (European Commission, 2019, 2021). On the other hand, considering the spread of the disease in the EU, China encourages bilateral applications for export licenses from EU MSs. In December 2021, a regional management agreement for ASF was signed, which is the first EU recognition of regionalisation. The deal allows France to export pork from unaffected regions, even if ASF has occurred elsewhere in France.

The different positions on the impact of regionalisation, in turn, reflect the different expectations for achieving sustainability goals in both trading partners. China's highly defensive position shows a high sensitivity to socio-economic concerns (food security) in a country characterised by a strong separation between pork production and consumption area (Yao *et al.*, 2022). For its part, the EU seeks to protect its pig industry for economic reasons, as it is the world's largest exporter of pigs and pig products and the second largest producer in the world after China, with a high concentration of pig meat production in a few MSs. The sector accounts for 8.5% of the total EU-27 agricultural output, the highest share of any meat sector (Augère-Granier, 2020). The STC shows a divergent perception of sustainable issues between the trading partners, one more pronounced on food security and the other on economic concerns. The length of STC, its recurrent nature, and the more general question of recognising regionalisation for managing outbreaks are clearly attributable to broader geopolitical tensions. The STC is still unsolved.

The EU-India case

The second STC concerns India's Phytosanitary import restrictions, due to the requirement of fumigation of plants and plant material with Methyl bromide (MBr). The STC was raised by the EU and the US (three times, all in 2004), supported by Canada, Chile, and New Zealand. MBr, as a fumigant, is recognised as an essential tool for controlling some quarantine pests of plants and plant-derived materials. At the same time, MBr is a powerful ozone-depleting gas. For these reasons, MBr is regulated by two Multilateral Agreements: the Montreal Protocol on Substances that Deplete the Ozone Layer and the IPPC. The production and consumption of MBr has been phased out worldwide by 2005 for developed countries and by 2015 for developing countries. There is an exemption to the ban for MBr for Quarantine and Pre-Shipment (QPS) use, considering the need for its use where there is no alternative. However, countries are encouraged to use options to MBr where they are technically and economically feasible. In the EU, the production and consumption of MBr for QPS purposes has been banned since March 2010, and MBr fumigation is not allowed for agricultural exports/imports. In 2004, a new import regulation came into force in India, requiring

[1] For details on trade barriers affecting EU exports to non-EU countries by the type of measures and by the product affected, see the DG Agri website https://trade.ec.europa.eu/access-to-markets/en/content/trade-barriers.

pre-shipment fumigation treatment with MBr for most plants and plant products. Because of the ban, India allowed fumigation on arrival in India until 2017. However, due to the thinning of the ozone layer over the country, India first withdrew and then reinstated permission for fumigation at Indian ports. Since 2017, periodically (every six months), India has been granting a waiver from using MBr in exporting countries and allowing fumigation on arrival, subject to payment of a penalty by exporters. Concerns have been raised about procedural issues – lack of predictability and transparency of import procedures, extra costs for paying penalties – and India's reluctance to accept alternatives to MBr.

The analysis of the EU-India STC looks at the trade-off effects of the SPS implemented by India, which focuses more on food security than climate change. In this sense, although the STC was formally raised due to problems with the harmonisation of procedures (including the imposition of penalties on exporters), the underlying sustainability issues reveal a different level of awareness/needs of the two partners. Continuous dialogue between the EU and India was conducted to resolve the STC regarding the procedural issues (payment of penalty lifted in 2022).

The Senegal-EU case

The third STC was raised by Senegal (once in 2008) for problems with control, inspection and approval procedures. It concerns the EU's restriction of mango imports from Senegal due to the interception of the fruit fly (an invasive pest considered the primary threat to the horticultural industry in Africa) in imports from Senegal. The mango sector in Senegal has grown dramatically in recent years, both in terms of production and exports. Still, its potential remains under-exploited due to the weakness of the production structures in the central Senegalese-producing regions. To strengthen measures to prevent the introduction and spread of harmful pests and diseases in the EU, a revised EU phytosanitary regime entered into force in December 2019, imposing additional requirements on all countries exporting mangoes to the EU (one of these is the submission to EU of a dossier detailing the "effective treatment" that is intended to be applied to all mango exports to ensure they are free from fruit flies). The EU and Senegal are working together to modernise the mango sector, make it compliant with the new EU SPS regulation, and continue exporting to the EU.

The case of Senegal is an example of cooperative behaviour between the two partners. Both partners are aware of the mango sector's importance in contributing to Senegal's sustainable economic growth and its potential to provide employment opportunities, particularly for women and young people, and to support rural communities by reducing poverty and ensuring decent work (Maertens and Swinnen, 2009; GIZ, 2021; COLEACP, 2022). The STC has been declared solved.

The analysis of the three STCs reveals that the two partners have different levels of awareness and needs regarding the underlying sustainability issues.We have identified three different behaviours regarding sustainability:

- divergent (EC-China case), because the two trading partners pose divergent sustainability goals on the same issue (regionalisation), China more pronounced toward food security and the EU on economic concerns (the defence of its pig industry) in an ongoing and not yet concluded discussion;
- negotiable trade-offs (EU-India case), because India presents a trade-off between sustainability objectives (food security vs climate change), focusing more on food security (the control of some quarantine pests of plants and plant-derived materials) while the EU on climate change (the effects of MBr on ozone layer); the two-trading partner reached a compromise solution on trade aspects;
- cooperative (Senegal-EU case) because the two trading partners share the same sustainability goals, that is, the importance of the mango sector in contributing to Senegal's sustainable economic growth. The STC is considered solved.

The next step will be to outline a path towards WTO modernisation in relation to sustainability through STCs, increasing the participation of less developed countries, following the principles of the ToC.

A way to WTO modernisation: the ToC

The second objective of our study is to present a pathway for modernising the WTO by investigating the links between trade and sustainability through a constructive and ongoing process of cooperation and consensus-building aimed at overcoming trade-offs and developing win-win situations.

This part of the work has been developed according to the logical framework of the ToC, which has dominated the institutional construction and capacity buildings of the major international agencies and agreements over the last decades (Vogel, 2012). The ToC is a methodology that assists organisations in planning, implementing, and evaluating initiatives to create social and environmental change (Lambert, 2023). It is conceived within the large framework of institutional change, and it is intrinsically connected to transition economics and economic development (Kingston and Caballero, 2009). This theory is beneficial for understanding, analysing and contributing to resolving international frictions. The key points of the ToC can be summarised as follows: 1) the theory attempts to hold together concepts such as context, actors and a sequence of logically-linked events leading to long-term change, although there may be many combinations and differently developed applications of these; 2) the approach is easily adaptable according to the nature, scope and level of detail of the change being implemented in different organisations and agencies; 3) the ToC is seen as a more realistic and flexible thinking tool than other current logical framework approaches. Following this theory, the main objective is to identify accelerators and enablers, bottlenecks and solutions to address bottlenecks to enhance the country's ability to prioritise actions to achieve sustainable issues along the three pillars of sustainability: economic, social and environmental.

Developing a comprehensive ToC requires a deep understanding of the underlying causes of a specific social issue. At the same time, it is important to acknowledge the diverse interventions addressing such causes. Practitioners should articulate their assumptions regarding how these interventions will lead to the desired outcomes. Additionally, they must create a precise plan for measuring and evaluating the impact of these interventions over time.

Furthermore, the ToC needs to be communicated to stakeholders. This is one of the most common issues raised in the good implementation of the ToC since it ensures that everyone involved in the project comprehends the strategy for effecting positive change in the system. Many stakeholders' inability to support and enhance linkages between activities and outcomes raises significant problems for the evaluation design (Connell and Kubisch, 1998). One of the most relevant factors in determining the feasibility of the ToC is the capacity of stakeholders and evaluators to identify, prioritise, and measure the key activities and contextual factors. The challenge posed by the theory of change approach is to theorise prospectively about these issues.

The construction of a specific ToC should drive organisations to identify risks and challenges associated with a particular initiative, create the conditions for mitigating those risks, and evaluate the impacts. So, the crucial point is that there is not a generalised ToC but a context-specific identification of a process: from the inputs to the outputs and the final outcomes of an evidence-based central activity (Figure 4).

The IPPC has also adopted the ToC approach, which aims to a deeper integration between the actors involved, with a view to introducing the principles of environmental and social sustainability and meeting the UN Millennium Development Goals. To achieve this, the only fruitful way is to analyse specific cases, set up a process of learning from experience, build some good practices to inspire and lead the way to further steps (Wolfe, 2020).

The foremost step of the ToC can be summarised in the following (Lambert, 2023):

1. Definition of the problem. Determine the causes of the problem and its main consequences. This phase involves research, stakeholder participation, and data collection to better understand the problem's causes.
2. Definition of impact goals and strategy (mapping solution). Once the problem has been identified, objectives and possible solutions must be defined through a logical model that defines the initiative's inputs, activities, outputs, and results. The model should be based on data collected and identify connections between activities and expected outcomes.
3. Identification of assumptions and risks. For the model to work well, it is important to identify all assumptions underlying the logical model and any potential risks that could affect the initiative's success. This will help develop strategies to mitigate risks.
4. Stakeholder engagement. Throughout the ToC's design process, it is important to involve stakeholders and collect feedback on their approach.
5. Definition of metrics for success. To monitor the initiative's progress and assess its impact, it is important to define evaluation metrics. This can be achieved through both quantitative and qualitative measures, such as the number of people reached, changes in behaviour or attitudes of those involved, improvements in health or well-being, etc.
6. Progress monitoring and evaluation. Once the ToC is implemented, monitoring and evaluating progress over time is important. This will help identify all areas where the approach can be adapted and where action can have the most significant possible impact.

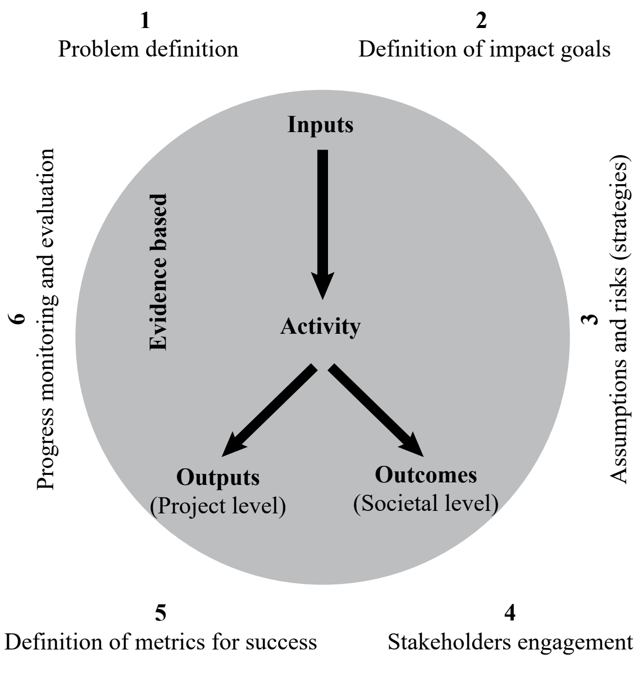

Figure 4: The theoretical representation of a context-specific ToC.
Source: Authors' elaboration

Discussion of the results

Considering the consensus on how to improve the use of STCs to reduce trade disputes to modernise WTO (Wolfe, 2020; Fabri *et al*., 2023; Posada *et al*., 2022) and keeping in mind the goal of fostering positive linkages between trade and sustainability, we try to add new evidence on the use of STCs to manage conflicts within the WTO following a ToC framework.

The STC mechanism is a process that has the potential advantage to enhance cooperation, transparency and surveillance, promote policy learning and best practices, engage economic diplomacy to clarify misunderstandings, create a dialogue between experts, and thus provide a space for cooperation (Santana and Dobhal, 2024; Fabri *et al*., 2023). So, our goal is not to apply a ToC framework to our cases but to read, through the lens of the ToC, the strengths and weaknesses of STCs as a conflict management tool in the WTO when sustainability issues are considered.

From the analysis of Table 2, in which the coherence of the three case studies examined with the steps of the ToC is highlighted, it emerges that the only case coherent with a ToC approach is the Senegal-EU, confirming the cooperative behaviour identified previously, in which the sustainability issues underlying the STC emerged from the very early steps (Problem definition). In this case, stakeholders (both public and private) of the two trading partners have cooperated to contribute to Senegal's sustainable economic growth by modernising the mango sector and making it compliant with the new EU SPS regulation. The clear understanding of the problem on which the two partners converge has allowed them to identify the correct strategy involving, also through technical assistance programmes, local actors and small producers. This is the only case solved of the three presented regarding sustainability issues. It is worth noting that many international development organisations developed a ToC to build a logical framework under which to develop a specific project (USAID, 2017; CORAF, 2018; World Bank, 2021) or to evaluate the program (IEO UNDP, 2023; Ministero degli Affari Esteri e della Cooperazione Internazionale, 2021).

EU-China and EU-India cases both appear inconsistent with the ToC framework. While the EU-India case is resolved on the trade side, it is not on the sustainability side, where the behaviour of negotiable trade-offs has emerged from the analysis in the above section. Both cases show weakness already in the definition of the problem (first step of the ToC), where it would be necessary to consider the (different) sustainability objectives of the two trading partners. This issue affects the subsequent steps regarding stakeholder engagement, as well as the definition of assumptions, risks, and strategy. The EU-China case is far from a solution both from a trade and sustainability point of view (it is the case where divergent behaviour emerges from the previous section). In both cases, there is a need to raise the level of ambition in bilateral economic and trade relations for sustainable development, involving stakeholders of a higher political level.

Table 2: Coherence of the three case studies with the ToC framework.

	EU-China (African Swine fever)	Coherence with the ToC	EU-India (Fumigation)	Coherence with the ToC	Senegal-EU (Mango)	Coherence with the ToC
1. Problem definition	Bring out the sustainability issues underlying STC	No	Bring out the sustainability issues underlying STC	No	Bring out the sustainability issues underlying STC	Yes
2. Goal definition and strategy	Goal definition Restart trade flows, responding to concerns about the safety of trade This contributes to achieving the sustainability objectives of partner countries (economic sustainability for the EU and food security for China)	Partial	Goal definition Restart trade flows, responding to concerns about the safety of flows while respecting EU concerns about climate change This contributes to achieving the sustainability objectives of partner countries (climate change for the EU and food security for India)	Partial Attention focused on trade barriers	Goal definition Contributing to Senegal's sustainable economic growth and its potential to provide employment opportunities, particularly for women and young people, and to support rural communities by reducing poverty and ensuring decent work	Yes
	Strategy - Enhancing cooperation and exchange of information - Increasing the level of ambition in bilateral economic and trade relations for sustainable development	Partial China promotes a Regional management agreement for ASF (like that signed with France in December 2021). This represents a point of vulnerability because China circumvents the problem by switching from a multilateral to a bilateral approach	Strategy Bring the discussion regarding climate change to the table	No Attention focused on food security only.	Strategy Modernise the Senegalese mango sector and bring it into compliance with the new EU SPS regulation.	Yes
3. Assumptions and risks	- Widespread scepticism about the effectiveness of regionalisation applied by the EU (many countries do not recognise EU regionalisation) - Spread of ASF in the EU Member states despite the regionalisation system	Yes	- Delays regarding the approval of alternative methods/products to MBr - Deriving from the fact that for India, the concern about short-term risks (pests) is predominant compared to medium/long-term risks (climate change)	Yes	Weakness of the production structures of the main Senegalese producing regions	Yes
4. Stakeholders engagement	Technical and political level of institutional stakeholders	No	Technical and political level of institutional stakeholders	No	Public and private sectors along the supply chain Local actors and small producers NGO and donors	Yes
5. Definition of metrics for success	STC is not solved on both the trade and sustainability sides, and recurrent	Elimination of the country-wide ban on imports from EU MSs where ASF was detected	STC partially solved on the trade side but not on the sustainability side	Reduction of MBr production and consumption for India's QPS purpose	STC solved both the trade and sustainability side	Continue exporting to the EU
6. Progress monitoring and evaluation		STC definitively solved		STC definitively solved		STC definitively solved

Source: Authors' elaboration

Conclusions

In recent years, the reduction of tariffs has been accompanied by an increasing use of NTMs in agri-food trade. SPS measures, which dominate in this field, are primarily intended to protect human, animal or plant life or health. Their trade-distorting potential causes increasing friction between countries that question the national implementation of SPS measures. Under the SPS Committee, a crucial role in defusing potential trade conflict is played by STCs considered a useful tool to be strengthened to modernise WTO.

For these reasons, exploring the sustainability issues underlying STCs and the different perceptions of these issues by trading partners through three case studies with the EU as a trading partner is crucial to identifying potential problems that standards and their implementation pose for trade with view sustainability issues. This topic is particularly relevant to the EU, given its central role in global trade and its particular sensitivity to the issue of sustainability in trade.

The analysis investigates the linkages between sustainability concerns in STCs and trade. One innovative element in pursuing this goal was applying the main steps of the ToC framework, which mainly highlights the processes through which change occurs. Through this lens, we could see and assess the effectiveness of building a link between trade and sustainability and to what extent this paves the way to further steps towards a synergic relationship between the two.

As SPSs are trade-restrictive measures introduced by a country to provide the level of health protection considered appropriate, the three case studies illustrate the importance of considering the sustainability issues underlying STC.

The analysis reveals three different behaviours: divergent, negotiable trade-off and cooperative. The exercise of reading the case studies through the lens of the ToC confirms the importance of taking sustainability issues into account to resolve STCs while contributing to reaching coherence among institutional levels and integration among different political fields. As a matter of fact, as shown in our study cases, only the cooperative behaviour between Senegal and the EU has proven to be more consistent with the application of a correct ToC. Correctly identifying the problem and engaging stakeholders in a participatory, collaborative and coordinated process could further improve the link between trade and sustainability and enable international trade to contribute to sustainable development. The other two cases seem inconsistent with the ToC framework, starting from defining the problem (first step) and affecting the subsequent phases. These two cases are the ones that have been going on the longest, have been raised numerous times and still remain unresolved (or partially solved but only from the trade point of view).

By definition, STCs bring with them sustainability issues, and if properly grounded to fully consider these issues, they can contribute to the resolution of frictions more easily and quickly. In this context, the ToC could be a way to manage STCs that brings together both trade and sustainability aspects, representing a path to dispute resolution and WTO modernisation through an incremental endogenous process of institutional change.

The work has been developed through a qualitative approach and a limited number of case studies. This limitation, however, is balanced by the diversity of the proposed cases, which are examples of three different behaviours of the trading partners, and by the possibility of applying the ToC to specific situations. The ToC is, in fact, built on this specificity and would not allow for a generalisation of the results. As reported in the introduction, the ToC is rather an analytical process rather than a complete and unique body of theory and a methodological framework. Future development of the work should focus on understanding the sustainability issues underlying STCs and how this can be used to resolve frictions between countries and prevent trade disputes, contributing to the modernisation of the WTO. Our analysis marks a significant advancement in developing a new approach to linking trade and sustainability. The preliminary results are not only promising but also suggest strong potential for further validation through additional research.

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Appendix

Table A1: An application of the ToC to our case studies dealing with trade and sustainable issues.

ToC steps	EU-China (African Swine fever)	EU-India (MBr Fumigation)	Senegal-EU (Mango)
1. Problem definition	The outbreak of ASF has impacted the world pork market and led to trade tensions between the EU and China. China imposes a country-wide ban on imports of pigs and pig products from EU MS where ASF has been detected, not recognising the EU regionalisation applied in accordance with WOAH. Currently, no vaccine is available. Prevention is the best way to avoid introducing infected material into ASF-free countries with adequate import policies and biosecurity measures. <u>Consequences</u>: • The ASF outbreak and trade restrictions have disrupted the global pork market, leading to a worldwide pork shortage, driving up prices, and affecting consumers worldwide. • The trade dispute has caused economic losses for both the EU and China, with declining exports, reduced revenues, and job losses in related industries. • Food safety is being questioned due to disruptions in the global pork market, particularly in regions that heavily rely on pigs as their protein source.	Due to India's strict import phytosanitary measures, particularly the use of MBr, countries willing to export plants and plant materials to India have faced unfavourable circumstances. Such barriers have also led to exporters' suffering in terms of additional costs and time. <u>Consequences</u>: • Cost increase: The use of MBr fumigation for exports to India, the regulatory issues involved, and the possible delays will adversely limit the returns from such exports. • Decline of the export market to core Countries: The sourcing market of exporting nations for plants and plant materials has shrunk because of India's phytosanitary barriers. • Fumigant-based MBr phase-out: The use of Mbr in fumigation due to the depletion of the ozone layer has also raised pertinent questions, and there is a clamour for its replacement with safer substances. • Damage to countries where India focused on extending trade relations	Senegal has endured losses and livelihoods for farmers and exporters due to the EU ban on mango imports from Senegal due to fruit flies. <u>Consequences</u>: • Losses: The EU ban caused massive losses to the Senegal mango export industry, farmers and exporters, and related businesses. • Livelihoods: Loss of income from mango exports has affected thousands of people in Senegal, mostly in rural areas. • Trade tensions: The trade dispute between the EU and Senegal has created tensions and strained relations.

<table>
<tr><th>ToC steps</th><th>EU-China (African Swine fever)</th><th>EU-India (MBr Fumigation)</th><th>Senegal-EU (Mango)</th></tr>
<tr><td>2. Definition of impact goals & Strategy</td><td>Objectives:
• Acceptance of the regionalisation principle
• Control ASF Outbreak.
• Restore Trade flows

Logical Model:
• Inputs: Funds invested in Research, development, and Maintenance, cooperation among international organisations and governments, and biosecurity.
• Activities: Research and development of ASF vaccines and diagnostic tools. Establishing biosecurity protocols on pig farms. Monitoring and surveillance of outbreak occurrences. Negotiating for ratifying treaties and common ground for regionalisation principle.
• Outputs: New vaccines for the control of ASF and diagnostic tools, agreed biosecurity protocols, ongoing trade measures and consequent evaluation of trade recovery.
• Results: Control of ASF outbreak. Ensuring a balanced pork market worldwide improves food security and animal health.</td><td>Objectives:
• Remove trade barriers
• Promote alternatives to MBr
• Enhance regulatory efficiency, reducing delays and uncertainties.
• Enhance bilateral cooperation

Logical Model:
• Inputs: Research and development of alternative pest control methods; coordination among international organisations and governments; evolution of regulatory infrastructure.
• Activities: Research and development of sustainable pest control alternatives; harmonisation of phytosanitary standards to international best practices; streamlining regulatory procedures; training and capacity building of regulatory authorities; information about climate change risks.
• Outputs: Sustainable and efficient pest management methods; reduced use of MBr; simplified and transparent regulation process; enhanced trade opportunities of India with other countries fetching national excise.
• Results: Reduced trade barriers for plants and plant material; enhanced environmental sustainability; strengthened bilateral relations and food security and agricultural development.</td><td>Objectives:
• Eradicate fruit fly infestation.
• Meet EU SPSs.
• Restore trade relations.

Logical Model:
• Inputs: Agricultural research, development and extension services; mango production and export infrastructure; Senegal-EU co-operation.
• Activities: Research on fruit fly control methods; implementation of good pest management practices; upgrading of export facilities and quality control systems; negotiation and implementation of trade agreements.
• Outputs: Fruit fly eradication in mango production areas; compliance with EU SPSs; capacity of Senegal's mango export industry; resolution of trade disputes and expected trade flows.
• Results: Increased mango exports from Senegal to the EU; improved livelihoods for farmers, rural areas and exporters; strengthened bilateral relations; food security and agricultural development.</td></tr>
<tr><td>3. Identification of Assumption & risk</td><td>Assumptions:
• The successful development of effective ASF vaccines and diagnostic tools is achievable.
• The implementation of stringent biosecurity measures can help to prevent disease from spreading entirely.
• The ASF outbreak and trade war battle will be won by international unity and collaboration.
• The trade crises between the EU and China will be solved to restore business as usual.

Risks:
• The likelihood of new strains of ASF virus that existing vaccines or diagnostics cannot control.
• Ineffective disease control procedures for pigs kept in farms that would no doubt trigger an outbreak.
• There is an increasing level of trade discord and retaliatory actions among the EU and China.
• Status quo on the recognition of regionalisation.
• Adverse impacts on the economies of both regions, such as loss of employment opportunities and fall in consumer confidence.</td><td>Assumptions:
• Alternative pest control methods can be developed, improved and effectively implemented.
• India is committed to reducing its reliance on MBr and improving its phytosanitary regulatory framework.
• International cooperation and collaboration will be sufficient to address the phytosanitary concerns, climate change issues and trade barriers.
• Both India and exporting countries are willing to compromise and find mutually beneficial solutions.

Risks:
• The development and improvement of alternative pest control methods may be challenging or time-consuming.
• India may face resistance from domestic stakeholders to changes in phytosanitary regulations.
• Trade tensions may escalate if the issue is not resolved promptly.
• The prolongation of the concern may results in an increased risk of climate change consequences</td><td>Assumptions:
• The fruit fly control strategy can be successfully established.
• Senegal's mango export industry can be brought to a new level of development and compliance with EU standards.
• The EU and Senegal are committed to improving the supply chain.
• The EU and Senegal are committed to solving the trade dispute and restoring expected trade flows.
• International cooperation and collaboration are good enough to handle the fruit fly infestation and trade barriers.

Risks:
• The emergence of fruit fly strains resistant to control methods might be problematic.
• Senegal's mango export industry may have problems complying with the EU SPSs requirements.
• The trade dispute may get worse. Hence, the economic losses for Senegalese farmers and rural areas might increase, and the bilateral relations might be even more strained.
• Climate change may worsen the fruit fly problem and make control efforts more difficult.</td></tr>
<tr><td>4. Stakeholders engagement</td><td>Stakeholders should participate in the process. In particular:
• Government officials of the EU and China who are in charge of agriculture, trade and health.
• Pork industry representatives: Producers, processors, and exporters in both regions.
• Science experts: Scientific and veterinary workers involved in ASF and animal health research.
• International organisations and NGOs.
• Consumer groups and environmental associations.</td><td>Stakeholders should participate in the process. In particular:
• Government officials of the EU and India who are in charge of agriculture, trade and environment.
• Agribusiness representatives: Producers, exporters and importers from both regions.
• Science experts: Pest control researchers and plant pathologists.
• International organisations and NGOs.
• Consumer groups and environmental associations.</td><td>Stakeholders should participate in the process. In particular:
• Government officials of the EU and Senegal who are in charge of agriculture, trade, rural areas and the environment.
• Mango industry representatives: Producers, exporters, and importers in Senegal and the EU.
• Science experts: Researchers and entomologists specialising in fruit fly control and phytosanitary measures.
• International organisations and NGOs.
• Local community representatives.
• Consumer groups and environmental associations.</td></tr>
<tr><td>5. Definition of metrics for success</td><td>Quantitative measures:
• ASF prevalence rates in the EU
• Pork production and consumption levels in China and the EU
• Trade volumes between the EU and China
• Economic indicators, such as GDP growth and employment rates

Qualitative measures:
• Level of compliance with biosecurity protocols
• Effectiveness of ASF vaccines and diagnostic tools
• Stakeholder satisfaction with the resolution of the trade dispute.
• • Improvements in food security and consumer confidence</td><td>Quantitative measures:
• Use of MBr in India for phytosanitary purposes.
• Compliance rates with phytosanitary regulations.
• Trade volumes between India and exporting countries for plants and plant material.
• Economic indicators, such as GDP growth and employment rates.

Qualitative measures:
• Effectiveness of alternative pest control methods.
• Stakeholder satisfaction with the resolution of the trade dispute
• Improvements in bilateral relations and cooperation.
• Environmental impact of phytosanitary measures.</td><td>Quantitative measures:
• Fruit fly infestation rates in mango production areas
• Trade volumes between Senegal and the EU for mango.
• Economic indicators, such as GDP growth and employment rates
• Compliance rates with EU SPSs.

Qualitative measures:
• Effectiveness of fruit fly control methods
• Stakeholder satisfaction with the resolution of the trade dispute
• Improvements in the quality and safety of Senegalese mango exports
• • Strengthened bilateral relations between Senegal and the EU</td></tr>
</table>

ToC steps	EU-China (African Swine fever)	EU-India (MBr Fumigation)	Senegal-EU (Mango)
6. Progress monitoring and evaluation	Evaluation Methods: • Data: Collect data on ASF prevalence rates, trade volumes, economic indicators, biosecurity measures and regionalisation recognition from governments, industry associations and research institutions. • Surveys and interviews: Conduct surveys and interviews with stakeholders on STC, effectiveness of regionalisation measures and satisfaction with regulatory processes. • Case studies: Analyse case studies of specific trade flows to identify challenges and opportunities of STC and regionalisation. • Expert reviews: Get expert opinions from scientists, economists and trade specialists on technical and economic aspects of the issue. Adaptive Evaluation: • Regular monitoring: Monitor the evaluation metrics to track progress and identify trends. • Data analysis: Analyse the data to identify areas of concern and improvement opportunities. • Feedback loops: Establish feedback loops with stakeholders to incorporate their inputs and suggestions into the evaluation process. • Adjustments: Be prepared to adjust STC, regionalisation measures or biosecurity protocols based on the evaluation results. Key Areas for Adaptation: • Regionalisation recognition: Continue to promote recognition of EU regionalisation by other countries through bilateral negotiations and international cooperation. • Biosecurity: Strengthen biosecurity in EU Member States to prevent further spread of ASF and improve regionalisation. • Trade facilitation: Find ways to facilitate trade between the EU and China, e.g., simplify regulatory procedures, and improve communication and cooperation. • Risk assessment: Conduct regular risk assessments to identify and address emerging threats to the pork industry, including new ASF variants or other diseases.	Evaluation Methods: • Data: Collect data on trade volumes, compliance rates, economic indicators and environmental impacts from government agencies, trade associations and research institutions. • Surveys and interviews: Conduct surveys and interviews with stakeholders to get their views on phytosanitary restrictions, alternative measures and satisfaction with the process. • Case studies: Analyse case studies of specific trade flows to identify challenges and opportunities with phytosanitary restrictions. • Expert reviews: Get expert opinions from scientists, economists and trade specialists to provide insights on the technical and economic aspects of the issue. Adaptive Evaluation: • Regular monitoring: Monitor the evaluation metrics to track progress and identify trends. • Data analysis: Analyse the data to identify areas of concern and opportunities for improvement. • Feedback loops: Establish feedback loops with stakeholders to include their insights and suggestions in the evaluation process. • Adjustments: Based on the evaluation findings, be prepared to adjust phytosanitary restrictions, alternative pest control methods, or the regulatory process. Key Areas for Adaptation: • Alternative pest control methods: Speed up the development and implementation of more environmentally friendly and effective alternative pest control methods. • Regulatory reform: Simplify and streamline phytosanitary regulatory procedures to reduce the burden on exporters and improve efficiency. • International cooperation: Work with exporting countries and international organisations to address phytosanitary concerns and find sustainable solutions. • Risk assessment: Conduct regular risk assessments to identify and prioritise emerging pest threats and develop mitigation measures.	Evaluation Methods: • Data: Collect data on the levels of fly infestation, trade indices, economic factors in the market, compliance rates, and production capacity from the government bodies, industry associations, and research institutions. • Surveys and interviews: Conduct surveys and interviews with stakeholders to get their views on the STC, the level of effectiveness of the phytosanitary measures, and the extent of their satisfaction with the regulatory processes. • Case studies: Analyse case studies of mango exports in order to pinpoint the issues and examine the ways of advancement caused by the STC and phytosanitary regulations. • Expert reviews: Get expert opinions from entomologists, economists, and trade specialists to probe the technical and economic aspects of the problem. Adaptive Evaluation: • Regular onitorimng: Monitor the evaluation metrics to track progress and identify trends. • Data analysis: Analyse the collected information to detect problematic regions and possibilities for improving the system. • Feedback loops: Establish feedback loops with the stakeholders to include their insights and suggestions in the evaluation process. • Adjustments: Based on the evaluation's findings, be prepared to adjust STCs, SPSs, or production processes. Key Areas for Adaptation: • Fruit fly control: Boost fly control measures through, among other things, the application of integrated pest management techniques and the development of new control technologies. • Production modernisation: Support the renewal of the Senegalese mango production sector through infrastructure, technology, and training investments. • Regulatory cooperation: Senegal's and the EU's cooperation will be enhanced to facilitate the SPS procedures and reduce trade barriers. • Sustainability: Promote sustainable practices in mango production, including using environmentally friendly inputs and conserving natural resources.

Source: Authors' elaboration

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Climate change and rice production: Empirical evidence from Vietnam

Vietnam has been one of the three largest exporting countries in the global rice market in the recent decades. This study conducts an in-depth analysis of the impact of climate change on rice production in Vietnam from 2002 to 2022, focusing on key climatic variables such as temperature, rainfall, sunshine, and humidity. Located in the tropical and subtropical monsoon climate, Vietnam's agricultural sector is acutely vulnerable to the growing challenges posed by climate variability. Employing robust empirical techniques, the research reveals significant correlations between climatic factors and rice yields. The findings demonstrate that rising maximum temperatures contribute positively to rice production while lowering minimum temperatures lead to reduced yields. Rainfall is shown to play a critical role in boosting productivity, whereas elevated humidity levels exert a detrimental effect. These results highlight the profound sensitivity of rice production to climatic changes, reinforcing the urgency for implementing adaptive measures and climate-resilient strategies to ensure the sustainability and stability of rice production in the face of a changing climate.

Keywords: rice production, agricultural output, climate change, cointegration test, Vietnam

JEL classifications: Q10, Q54.

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Introduction

Vietnam, centrally located in Southeast Asia and classified as an emerging economy, is already experiencing the harmful effects of climate change (Vo and Tran, 2022). With its large extent of coastline, heavy dependence on agriculture - especially in the Mekong Delta region - and situated in the Southeast Asian tropical monsoon belt, it is exposed to high precipitation and storms (Cullen and Anderson, 2017). More frequent natural disasters will shortly influence crop productivity, food security, and livelihood vulnerability. Climate change is significantly impacting livelihoods in Vietnam, affecting agriculture, tourism, health, fisheries, natural resources, and vulnerable groups. Changes in water temperatures and ocean conditions pose risks to fisheries and aquaculture, affecting fish populations and distribution (Tchonkouang *et al.,* 2024). Extreme weather events and environmental degradation harm tourist destinations, leading to increased heat-related illnesses and healthcare costs due to extreme temperatures (Effiong *et al.,* 2024) and might reduce GDP by 0.7%–2.4% by 2050 (Trinh *et al.,* 2021). Within the last two decades, the average temperature has been 0.72°C higher than in the period 1962–1990 for Northeast Vietnam (Kawagoe *et al.,* 2019). This increase in temperature could lead to a reduction in the rice growth period, which will negatively affect the absorption of some major nutrients. A 1% increase in temperature will cause a short-run drop of approximately 0.67% in rice production and 2.74% in the long run (Chandio *et al.,* 2024). In Vietnam's Mekong Delta, saltwater intrusion could harm 1.1 million hectares, or 70% of cultivated land, by 2030. A 30 cm sea level rise by 2050 might inundate 193,000 ha of rice cultivation area and salinity incursion 294,000 ha, reducing rice production by 2.6 million metric tons (Trinh *et al.,* 2021). Given Vietnam's major share in the global rice market, a drop in agricultural output could result in deteriorating regional and worldwide food shortages.

Rice cultivation faces two major challenges: feeding an ever-increasing population and adopting mitigation measures against the adverse effects of climate change through sustainable agriculture (Hussain *et al.,* 2020). As the population increases and the climate changes, the interaction between rice cultivation and climate becomes increasingly relevant, influencing arable land and crop productivity (Taniushkina *et al.,* 2024). To address these challenges, it is essential to understand how climate conditions affect rice growth and yields to design effective measures for sustaining rice production. Crop yield increment is on the main agenda for most local rice growers. This is attained by the introduction of new cultivars and reviewing existing practices in the areas of planting with a view to optimising the use of fertilisers and pesticides (Shabbir *et al.,* 2020; Nhat Lam Duyen *et al.,* 2021). However, high yields in rice cultivation require suitable natural conditions relating to humidity, temperature, sunshine, and rainfall (Firdaus *et al.,* 2020; Ding *et al.,* 2020).

In high-latitude regions, rising temperatures have improved rice yields by creating better thermal conditions in areas where low temperatures previously limited production (Liu *et al.,* 2022). In contrast, low-latitude regions, such as Vietnam, have experienced negative impacts as crops in these areas are closer to their temperature tolerance limits (Chen *et al.,* 2020). The effects of rainfall variability on rice production vary significantly across different regions and even within specific geographical areas. This can, to a very large extent, be explained by local climate, water management, and farmers' adaptation strategies and these aspects, however, require more attention with further research (Chandrasiri *et al.,* 2020;

Firdaus *et al.,* 2020). As such, there is a greater call for experimental studies conducted in various regions, especially in low-latitude regions like Vietnam, in order to understand how climatic change impinges on rice productivity.

Numerous studies have examined the impact of climate change on rice production (Wassmann *et al.,* 2009a; Yang *et al.,* 2017; Tan *et al.,* 2021; Zhou *et al.,* 2021; Yin *et al.,* 2022; Wei *et al.,* 2023), where most concentrate on specific regions and often neglect critical variables. While temperature and rainfall are frequently analysed (Chandio *et al.,* 2021), there are very few studies investigating the influence of climatic factors such as sunshine, wind, CO2, and humidity on crop yields (Tchonkouang *et al.,* 2024). Moreover, much research has employed crop simulation models and field trials (Ding *et al.,* 2020; Chandio *et al.,* 2021); nevertheless, econometric methods have largely been overlooked. For Vietnam, some studies have examined the influence of climatic changes on rice production (Ho *et al.,* 2022; Vo and Tran, 2022), food security (Taniushkina *et al.,* 2024), adoption of climate-smart agriculture technologies (Tran *et al.,* 2022; Chandio *et al.,* 2024) and rice farmers' perceptions (Do Thi and Dombroski, 2022). To the best of the authors' knowledge, however, none of the available studies have examined the combined effects of climatic factors, including sunshine, rainfall, humidity, and temperature, on rice productivity in the country. Accordingly, the present study aims to examine the combined influences of climate change on rice production in Vietnam.

This study addresses two key questions. First, how does climate change impact rice production? Second, what role do climatic factors – such as temperature, sunshine, rainfall, and humidity – play in enhancing rice production in Vietnam? The findings can serve as a reference for developing countries with similar economic and climatic conditions.

This study makes three important contributions. First, the study is the first of its kind to measure the impacts of climatic factors – temperature, sunshine, rainfall, and humidity – on the rice yield of Vietnam. Second, using the cointegration test method, the study provides valuable insights for Vietnamese policymakers to boost rice exports and enhance domestic production by applying the findings. Lastly, the current study delivers an in-depth investigation into the subject and some relevant policy implications to guarantee food security and prepare farmers for the constantly changing climate.

The following sections are organised as follows: Section 2 provides a critical review of the literature. Section 3 discusses methodology and data sources. Sections 4 and 5 present the empirical findings and their interpretation. Finally, Sections 6 and 7 conclude the study with discussions and policy implications.

A brief literature review of climate change and rice production

Climate change is defined as the shift in climate patterns primarily caused by greenhouse gas emissions (Fawzy *et al.,* 2020). The impact of global warming would be an increase in the average surface temperature worldwide. This rise in temperature will then affect the hydrological cycle shifting precipitation amounts, intensity, frequency, and type of precipitation. It will also affect the amount of water vapour available within the atmosphere, thereby affecting humidity. Additionally, global warming would change atmospheric circulation and could alter wind speeds. Therefore, the climatic effects of global warming involve a much larger set of variables than just temperature and precipitation (Zhang *et al.,* 2017). The causes of climate change range from natural factors to anthropogenic factors. Natural sources encompass or linked to forest fires, earthquakes, oceans, permafrost, wetlands and volcanoes (Xi-Liu *et al.,* 2018). In contrast, human activities are mainly related to energy production, industrial processes, forestry, land use and land-use change (Yadav *et al.,* 2021).

Ninety percent of the world's rice is produced and consumed in Asia, where both irrigated and rain-fed rice ecosystems are vital for food security (Wassmann *et al.,* 2009b). Climatic changes are already affecting agriculture, but there are still major lacunae in the understanding of how both short- and long-term climatic changes influence agricultural systems and rural livelihoods, especially for the most vulnerable populations (Yadav *et al.,* 2021). Although climate change is very likely to create some opportunities for increased production in certain regions and for specific crops, the overall impact is expected to be that of decreased agricultural outputs (Chandio *et al.,* 2021).

Pattern changes in precipitation and temperature, as reported globally, affect crop production to a great extent. This is especially so in developing regions, where economies are based on agriculture, as unprecedented climate change disrupts the economic and social sectors (Firdaus *et al.,* 2020). Dependence on climate-sensitive agriculture, coupled with limited adaptive capacity and existing socioeconomic inequalities, amplifies the impacts of climate change on nations, and those countries in lower latitudes with agrarian economies are facing especially increased vulnerability (Chakravarty *et al.,* 2020). This arises from a combination of factors, including the susceptibility of agriculture to climate change (Trinh *et al.,* 2021). Coastal erosion, increased flooding from storm surges, and saltwater intrusion into freshwater sources are major risks that further threaten livelihoods, infrastructure, and freshwater availability (Taniushkina *et al.,* 2024). This sensitivity to temperature changes is especially pronounced in regions where temperatures are already approaching the tolerance levels of staple crops, exacerbating the impacts of global warming (Firdaus *et al.,* 2020). Climate change disproportionately impacts vulnerable populations, pushing them further into poverty and food insecurity. These populations often lack the resources and capacity to adapt to climate change and make them more susceptible to displacement, food shortages, and economic hardship (Aryal *et al.,* 2020).

The effect of temperature increases on crop growth has been estimated from crop simulation and statistical analysis. A rise in temperature of 1% in both time horizons decreases rice yield by 1.01% and 2.99%, respectively (Anh *et al.,* 2023). High temperatures each day reduces rice yields by about 6% per °C if they deviate away from the ideal 28 °C. High temperatures every night have an even more significant negative influence as decreasing the yield with approximately 7% per °C if deviating from the ideal 22 °C of night-time temperature. The minimum temperature positively affects rice plants at the vegetative stage of replanting, while the maximum temperature hurts rice plants at the tillering and stem elongation stages (Abbas and Mayo, 2021). Besides this, high night-time temperatures are also related to adverse spill-over effects like milling yield and grain quality, decreasing the percentage of milled, head, and brown rice and increasing chalkiness, with the latter also coinciding with decreased contents of amylose and protein (Su *et al.,* 2023). In contrast, other studies have found that in some regions even the net effect was positive due to a moderate increase in temperature like that Northeast China faced until recently (Liu *et al.,* 2022). This distinction is very important because in most of the rice-growing areas across the world, the pace of increment in night-time temperature is very fast compared to that of the daytime temperature (Su *et al.,* 2023).

The effect of sunshine on rice yield varies over geographical areas and latitudes. Sunshine is an important weather variable in a tropical country, while changes in sunshine significantly influence crops and yields throughout the growing seasons (Firdaus *et al.,* 2020). More sunshine in north-eastern China might lead to an expansion of rice cultivation because of the increased thermal resources in colder climates like this part of China (Chen *et al.,* 2020). On the other hand, in places where the climate is hot, too much sunshine doesn't guarantee increased yield and could even have detrimental effects (Anh *et al.,* 2023). This variation underscores the importance of considering regional specificity when assessing the impact of sunshine on rice production. Solar radiation is one of the most crucial energy sources affecting crops, significantly influencing rice yields, especially during the final 35–45 days of grain ripening (Lee *et al.,* 2021). This effect is more prominent when other factors like water, temperature, and nutrients are not limited. At the ripening stage, rice needs sufficient radiation and low temperatures (Hussain *et al.,* 2020). There is a positive correlation between increased sunshine, net solar radiation and potential rice yields. In some cases, a lower average shortwave solar radiation during the growing season might increase rice yields by approximately 3% (Chen *et al.,* 2020).

One of the most important indicators for the change in climate is rainfall as it highly affects the production of rice. On the other hand, increased precipitation often leads to frequent and heavy flooding. This has been experienced in some of the most extensive rice-growing regions, such as the Mekong Delta, where the frequency of rainfall is more erratic towards the end of the wet season, which increases the chance of inundation (Ho *et al.,* 2022). The damage caused by such floods to crops and overall production is immense, as observed in Malaysia, where the floods in 2003, 2005, and 2017 resulted in significant losses in rice production, impacting farmers' livelihoods and food security at the national level (Firdaus *et al.,* 2020).

In contrast, low rainfall can cause the complete loss of harvest in areas where minor irrigation tanks dependent on rainfall are being used. Changes in rainfall can affect rice production directly due to changed rainfall, mainly reduced rainfall, through the abandonment of fields or a reduction in planting in case of inadequate water supply as was found in a study carried out in Sri Lanka (Firdaus *et al.,* 2020). The impacts of rainfall variability on rice production can vary significantly across different regions and even within specific geographical areas. While this is substantially explained by local conditions of climate, water management practices and adaptation strategies adopted by farmers, further investigation is required on these topics (Chandrasiri *et al.,* 2020; Firdaus *et al.,* 2020). Nevertheless, other research has shown the opposite findings. For example, Abbas and Mayo's study from 2021 found that rainfall negatively affects rice plants throughout the flowering and heading stages. Rainfall's detrimental effects on rice production were also noted during the ripening period when the rice was being milked. During the reproductive stage, rainfall notably affected the per capita gross domestic product (Abbas and Mayo, 2021).

Humidity directly and indirectly affects rice growth. It directly affects the water vapour content in the troposphere which can further influence photochemical reactions and thermal processes and eventually alter plant growth (Yadav *et al.,* 2021). In addition, it also impacts the plant's water content. Indirectly, humidity impacts leaf growth, photosynthesis, pollination, and the likelihood of disease (Zhang *et al.,* 2017). It impacts photosynthesis through changes in transpiration. Excess moisture increasingly co-occurs within a single growing season, impacting crop yields in global rice-growing regions (Lesk *et al.,* 2022). The higher humidity results in a reduction in transpiration and an increase in the turgor pressure, favoured by leaf expansion (Zhang *et al.,* 2017). Low humidity triggers increased transpiration, leading to water deficits that cause stomata to partially or fully close, restricting carbon dioxide intake and consequently hindering the process of photosynthesis (Zhang *et al.,* 2017). Newly harvested rice may contain about 18–26% water, and managing very wet rice at harvest time is a serious issue in most Asian countries, as high humidity can promote excessive mould growth and increase respiration rates in the grain (Tirawanichakul *et al.,* 2004).

Methodology

Climate change is significantly affecting agricultural production in Vietnam, and particularly rice cultivation, one of the country's key export commodities. Beyond its economic importance, rice farming is vital for rural livelihoods and provides extensive employment opportunities across Vietnam's rural areas. To measure the impact of climate change on rice production, several econometric models have been used. These models analyse three main dependent variables representing rice output: spring season yield, winter season yield, and annual yield.

$$T\_Rice_{it} = \lambda_0 + \lambda_1 Temperature\_max_{it} + \lambda_2 Temperature\_min_{it} + \lambda_3 Rainfall_{it} + \lambda_4 Sunshine_{it} + \lambda_5 Humidity_{it} + \varepsilon_t \quad (1)$$

$$S\_Rice_{it} = \beta_0 + \beta_1 Temperature\_max_{it} + \beta_2 Temperature\_min_{it} + \beta_3 Rainfall_{it} + \beta_4 Sunshine_{it} + \beta_5 Humidity_{it} + \xi_t \quad (2)$$

$$W\_Rice_{it} = \alpha_0 + \alpha_1 Temperature\_max_{it} + \alpha_2 Temperature\_min_{it} + \alpha_3 Rainfall_{it} + \alpha_4 Sunshine_{it} + \alpha_5 Humidity_{it} + \sigma_t \quad (3)$$

The econometric models incorporate key climate change variables, including maximum and minimum temperature, rainfall, sunshine, and humidity in order to analyse the effects on rice yield. The estimation process follows three key steps. First, a correlation matrix analysis is conducted to examine the initial relationships among the variables. Second, to test for long-term cointegration between the variables, we employ panel cointegration tests, such as those by Pedroni, Kao, and Westerlund. According to Kao's cointegration test (Kao, 1999), the cointegration vectors in each panel are assumed to be identical. To supplement this, the authors include the Pedroni test, which allows the AR coefficients to differ between panels by permitting specific cointegration vectors. Pedroni (2004) states that tests based on clustering are considered multivariate, whereas tests based on grouping-panel statistics are called univariate.

The Westerlund test is based on the idea that each panel has its own unique slope coefficient and that the cointegration vectors are panel-specific. Models where the AR parameters are either panel-specific or consistent across panels form the foundation for the Westerlund (2005) test statistic. In this instance, the hypothesis of no cointegration is tested against the alternative hypothesis using the panel-specific AR test statistic. In contrast, the null hypothesis of cointegration is tested using the same AR test statistic (Westerlund, 2005), which asserts that all panels are cointegrated. The authors have selected the Pedroni, Westerlund, and Pedroni tests as the primary tests in the econometric models because of their comprehensive approach to cointegration testing. Third, we assess the models for diagnostic issues, including autocorrelation and heteroskedasticity. We apply the Pooled OLS method for estimation. However, if autocorrelation or heteroskedasticity is detected, the Driscoll-Kraay standard errors method is used to address these problems and estimate the functions more robustly (Driscoll and Kraay, 1998).

The data for this study were sourced directly from the official website of the General Statistics Office of Vietnam (GSO, 2024). We compiled a panel dataset from 15 provinces across Vietnam, including Lai Chau, Son La, Tuyen Quang, Hanoi, Quang Ninh, Nam Dinh, Nghe An, Thua Thien-Hue, Da Nang, Binh Dinh, Gia Lai, Lam Dong, Khanh Hoa, Ba Ria - Vung Tau, and Ca Mau. The dataset spans the period from 2002 to 2022. Because GSO has public representative agencies for collecting data in all provinces of Vietnam, this database does not have any issues such as missing data or reporting bias. Detailed definitions and units of the variables used in the analysis are provided in Table 1.

First, we discuss the descriptive statistics of rice yield. The total annual rice yield in 15 provinces has an average value of 103.2 quintals/ha. However, rice yield according to weather characteristics is different for each crop season. Spring and winter rice yields have average values of 95.97 quintals/ha and 39.83 quintals/ha, respectively. This shows that rice yield fluctuates strongly according to weather where the relatively harsh winter climate in some provinces decreases rice yield. Second, related to climate change, the maximum temperature has an average value of 28.57^{0}C and this index also fluctuates during the annual seasons with temperatures between 19.1^{0}C and 32.8^{0}C. The rainfall statistics have an annual average value of 164.4mm/month, but this index fluctuates significantly according to the times of the year from 67.25mm/month to 401.0mm/month. The average sunshine duration is 160.6 hours and this index has also a significant amplitude of fluctuation where the minimum value is 13.84 hours and the maximum value is 244.8 hours. Humidity in the provinces has the lowest value of 2.88%, and the highest is 88.41%, which is close to the average value of 81.21%.

Table 3 shows the correlation values between rice yield and the variables representing climate change in the econometric equations. Based on the Pearson correlation analysis, maximum temperature has a positive relationship with total rice yield (0.274), spring rice yield (0.138) and winter rice yield (0.112) where all the correlations of maximum temperature with rice yield are statistically significant. Minimum temperature is only significantly related to spring rice yield (-0.243) and winter rice yield (-0.125), where both

Table 1: Definition and unit of variables.

Variable	Definition and unit	Unit
T_Rice	Production of rice by province (calculated by total yield)	Quintal/ha
S_Rice	Production of rice by province (calculated by spring rice yield)	Quintal/ha
W_Rice	Production of rice by province (calculated by winter rice yield)	Quintal/ha
Temperature_max	Maximum temperature	^{0}C
Temperature_min	Minimum temperature	^{0}C
Rainfall	Monthly average rainfall	mm
Sunshine	Monthly average sunshine	Hour
Humidity	Monthly average humidity	%

Source: Authors' compilation

Table 2: Descriptive statistics.

Variable	Mean	Std. Dev.	Min.	Max.	Observations
T_Rice	103.2	56.10	1.000	197	315
S_Rice	95.97	50.71	1.000	187	315
W_Rice	39.83	11.95	10.00	65.0	315
Max_temperature	28.57	2.951	19.10	32.8	315
Min_temperature	19.81	4.190	12.40	27.0	315
Rainfall	164.6	52.58	67.25	401.0	315
Sunshine	160.6	39.13	13.84	244.8	315
Humidity	81.21	2.883	2.880	88.41	315

Source: Authors' calculation

Table 3: Correlations among variables.

Variable	*T_Rice*	*Max_T*	*Min_T*	*Rainfall*	*Sunshine*	*Humidity*
T-Rice	1.000					
Max_T	0.274*	1.000				
Min_T	-0.042	0.318*	1.000			
Rainfall	0.138*	-0.086	-0.004	1.000		
Sunshine	-0.181*	-0.363*	0.530*	-0.085	1.000	
Humidity	-0.022	0.011	-0.052	0.439*	-0.240*	1.000
Variable	*S_rice*	*Tmax*	*Tmin*	*Rainfall*	*Sunshine*	*Humidity*
S-Rice	1.000					
Max_T	0.138*	1.000				
Min_T	-0.243*	0.318*	1.000			
Rainfall	-0.019	-0.086	-0.004	1.000		
Sunshine	-0.136*	-0.363*	0.530*	-0.085	1.000	
Humidity	-0.165*	0.011	-0.052	0.439*	-0.240*	1.000
Variable	*W_rice*	*Tmax*	*Tmin*	*Rainfall*	*Sunshine*	*Humidity*
W-Rice	1.000					
Max_T	0.112*	1.000				
Min_T	-0.125*	0.318*	1.000			
Rainfall	-0.226*	-0.086	-0.004	1.000		
Sunshine	-0.188*	-0.363*	0.530*	-0.085	1.000	
Humidity	-0.253*	0.011	-0.052	0.439*	-0.240*	1.000

Note: adenotes statistical significance at the 5% level. Max_T is the Maximum temperature, Min_T is the Minimum temperature.
Source: Authors' calculation.

coefficients are negative. Rainfall has a positive and statistically significant relationship with total annual rice yield (0.138). However, rainfall has a statistically significant negative relationship with winter rice yield (-0.226), while spring rice has a negative insignificant relationship (-0.019). Sunshine has a negative and significant relationship with rice yield and this holds for total rice yield (-0.181), spring rice (-0.136) and also winter rice (-0.188). Finally, the correlation between humidity and total rice yield is negative and insignificant (-0.022), but significant in the cases of spring rice (-0.165) and winter rice (-0.253). The absolute values of the correlation coefficients in the table are not very high, but all variance inflation factors (VIF) are below 5, which indicate that the problem of multicollinearity does not appear to be a major problem in the estimations.

Results

The dataset includes numerous socioeconomic variables, some of which may exhibit stochastic trends, potentially leading to spurious inferences if not properly addressed. To ensure reliability, we check whether the panel data are stationary - that is, whether its statistical properties, such as mean and variance, remain constant over time. If the data are non-stationary, it contains a unit root, which can affect the validity of the results. Before estimation of the agricultural yield equations, we test all variables for stationarity to identify whether they are stationary at the original level (denoted as I(0)) or become stationary after differencing once (denoted as I(1)). There are two hypotheses in the testing exercises; the null hypothesis (H0) of the existence of a unit root is tested against the alternative hypothesis of no unit roots (H1). We conduct three unit root tests, which are the Breitung test, the Harris–Tzavalis test, and the PP—Fisher Chi-square test. These tests evaluate the null hypothesis (H_0) that a unit root exists (i.e., the data is non-stationary) against the alternative hypothesis (H_1) that the data are stationary.

Table 4 shows that the variables are stationary at their first differences, with significance levels of 1% or 5%. This confirms that the variables are integrated of order one, I(1), and supports the use of cointegration tests to examine long-term relationships between variables. Cointegration refers to a statistical property where non-stationary variables move together over time, maintaining a stable long-term relationship despite short-term fluctuations.

Table 4: The panel unit root test for the variables.

Variable	**Im–Pesaran–Shin test**		**Levin–Lin–Chu test**		**Breitung test**	
	Level I(0)	**First difference I(1)**	**Level I(0)**	**First difference I(1)**	**Level I(0)**	**First difference I(1)**
T_Rice	2.4361	-6.6326[a]	-3.6653[a]	-19.6970[a]	2.3169	-2.0864[b]
S_Rice	1.0957	-6.0295[a]	-1.7815[b]	-19.6837[a]	2.2177	-2.1567[b]
W_Rice	-0.0727	-9.3365[a]	-7.9550[a]	-17.8898[a]	1.5390	-2.4441[a]
Max_temperature	-0.2710	-7.0987[a]	-2.6397[a]	-9.7565[a]	-1.4969[c]	-2.5238[a]
Min_temperature	-1.2472	-7.0638[a]	-4.5619[a]	-9.8534[a]	-3.7752[a]	-6.2562[a]
Rainfall	-2.8225[a]	-7.5629[a]	-10.6426[a]	-24.4091[a]	-1.3324[c]	-3.5474[a]
Sunshine	-2.7564[a]	-7.0628[a]	-10.0847[a]	-22.2293[a]	-3.0135[a]	-4.0091[a]
Humidity	-1.9694[b]	-7.4629[a]	-7.4666[a]	-20.0299[a]	-2.8399[a]	-2.3545[a]

Notes: [a] , [b] and [c] indicate significance at 1%, 5%, and 10%, respectively.
Source: Authors' calculation

The panel unit root tests confirmed that all the variables in equations (1), (2), (3), and (4) are integrated at the same order, specifically I(1). In the next step, we will test whether there is a cointegration relationship between the variables in the above equations. For this purpose, cointegration tests are used to test the long-run relationship between the variables. We use Pedroni (1999), Kao (1999), and Westerlund and Edgerton (2007) cointegration tests for checking the long-run relationship between the variables. Four agricultural productivity equations will be tested in this section where all the equations are tested step by step. Table 5 shows the results of the cointegration tests. The null hypothesis (H_0) of no long-run cointegration is rejected when these statistics are significant at the 1% level. The results provide strong evidence supporting the existence of long-run relationships among the variables in all four equations, confirming their interconnectedness over time.

The cointegration test results reported in Table 5 conclude that all variables in the research equations are cointegrated. In the next step, we will determine the quantitative relationship between climate change variables (rainfall, sunshine, temperature and humidity) and rice yield (total yield, spring rice yield, winter rice yield) by estimating panel data regression models.

Before initiating the panel estimation process, we first check all output equations assessing the impact of climate change on rice yield for heteroscedasticity (unequal variance in the error terms) and autocorrelation (correlation of error terms across time). If these problems are not detected, the equations will be estimated using Fixed effects and Random effects methods. If the equations suffer from heteroscedasticity and autocorrelation, the Driscoll-Kraay standard error method will be used to estimate the coefficients of the variables. This method is specifically designed to address these issues by adjusting the standard errors, ensuring more reliable estimates. It allows for accurate assessment of the statistical significance of the coefficients, even when the error terms exhibit varying sizes or temporal correlation.

Table 6 shows the results of heteroscedasticity and autocorrelation tests. The Breusch–Pagan/Cook–Weisberg test is used to test heteroscedasticity and the Wooldridge test runs for autocorrelation problems. Based on the test results, the equations of rice yield and climate change are free of heteroscedasticity and autocorrelation. Then, the equations will be estimated using Fixed effects (FEM) and Random effects (REM) methods. The Hausman test is performed to choose between FEM and REM.

After conducting autocorrelation and heteroscedasticity tests, we found no evidence of these issues in the model. The Hausman test confirmed that the REM model provides better explanatory power and the empirical results from the REM estimation on rice yield and climate change effects are presented in Table 7.

Table 5: Panel cointegration test results.

Equation	Statistics	P-value
Pedroni cointegration test		
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	4.1154	0.0000
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	4.2727	0.0000
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	4.0635	0.0000
Kao cointegration test (Augmented Dickey–Fuller)		
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	3.3968	0.0003
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	3.8383	0.0001
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	2.7132	0.0033
Westerlund cointegration test		
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	18.0806	0.0000
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	15.0844	0.0000
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	13.0845	0.0000

Note: Kao test using the Augmented Dickey-Fuller. Pedroni test using Modified Phillips–Perron.
Source: Calculates from the study data

Table 6: Diagnostic testing results.

Function	Heteroskedasticity	Autocorrelation
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	$\chi^2(1) = 0.30$ P-value = 0.5811	F(1,14) = 3.461 P-value = 0.0840
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	$\chi^2(1) = 2.19$ P-value = 0.1390	F(1,14) = 4.472 P-value = 0.0529
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	$\chi^2(1) = 0.68$ P-value = 0.4089	F(1,14) = 3.469 P-value = 0.0837

Notes: Heteroskedasticity was assessed using the Breusch–Pagan/Cook–Weisberg test, while autocorrelation was evaluated using the Wooldridge test.
Source: Authors' calculation.

Table 7: The panel estimates for the models.

Independent variable	Model 1: T_Rice		Model 2: S_Rice		Model 3: W_Rice	
	Fixed effects	Random effects	Fixed effects	Random effects	Fixed effects	Random effects
Max_temperature	5.580[a]	5.740[a]	4.783[b]	5.191[a]	0.677[c]	0.674[b]
Min_temperature	-5.427[a]	-5.063[a]	-4.898[a]	-5.141[a]	-0.850[a]	-0.830[a]
Rainfall	0.163[a]	0.168[a]	0.186[a]	0.182[a]	0.014	0.013
Sunshine	0.177	0.177	0.200[c]	0.197[c]	0.013	0.011
Humidity	-4.590[a]	-4.302[a]	-5.997[a]	-5.736[a]	-0.647[a]	-0.672[a]
Constant	368.7[a]	332.6[b]	480.3[a]	453.4[a]	85.40[a]	87.59[a]
R^2	0.1125	0.1121	0.1348	0.1347	0.0632	0.0630
F test (P value>F)	35.36 (0.000)		22.49 (0.000)		65.11 (0.000)	
Hausman test (P value>χ^2)		1.39 (0.9249)		0.62 (0.9870)		1.63 (0.8976)
Provinces	15	15	15	15	15	15
Observations	315	315	315	315	315	315

Notes: [a], [b] and [c] indicate significance at 1%, 5%, and 10%, respectively.
Source: Authors' calculation.

First, the maximum temperature has a very positive impact on rice yield and is statistically significant for total rice yield (5.740), spring rice (5.191), and winter rice (0.674), respectively, at the significance level of 5% and 1%, which is consistent with the study of Liu *et al.* (2022). The closer the temperature is to the maximum, the better the rice yield. However, this impact will be stronger in spring rice, when warm weather is a favourable factor for rice growth and development.

Second, the minimum temperature has the opposite effect of negatively influencing rice yields. The regression results show that the minimum temperature affects rice yield for total rice (-5.063), spring rice (-5.141), and winter rice (-0.830), at the significance level of 1%. The impact of minimum temperature will be more significant for winter rice, and this shows that the lower the temperature, the lower the rice yield. Winter, when temperatures become more severe, will reduce the rate of photosynthesis, chlorophyll fluorescence, and dry matter characteristics, contributing to reduced rice yield (Siddik *et al.,* 2019).

Third, rainfall is a positive factor in rice yield; the impact level is respectively with total rice yield (0.168), spring rice (0.182), and winter rice (0.013). However, only the impact of rainfall on total rice yield and spring rice yield is statistically significant at the 1% level. Higher rainfall can lead to improved rice yield. Conversely, when rainfall decreases, the impact will be harmful, and insufficient water supply will cause reduced crop yields (Firdaus *et al.,* 2020).

Fourth, the impact of sunshine on total rice yield is (0.177), spring rice (0.197), and winter rice (0.011). Sunshine has a positive effect on rice yields. However, in the experimental results in Table 7, only spring rice is statistically significant at the 10% level. sunshine has a positive impact on rice yield, this result is completely consistent with the study of Chen *et al.* (2020). One of the most important energy sources for crops is solar radiation, which has a major impact on rice yields, particularly in the last 35 to 45 days of grain ripening (Lee *et al.,* 2021).

Finally, humidity has a negative impact on most rice yields. Specifically, humidity reduces total rice yield (-4.302), winter rice (-5.736), and winter rice (coefficient = -0.672). All coefficients of humidity impact on rice yield are significant at the level of 1%. This shows that increasing humidity in the air will be a harmful factor for rice yields. Humidity further affects plants' photochemical reactions and thermotrophic processes and alters plant growth (Yadav *et al.,* 2021).

Discussion

Climate change poses a significant threat to global agriculture with rice production being particularly vulnerable (Gomez-Zavaglia *et al.,* 2020; Wassmann *et al.,* 2009a). As one of the most important staple crops in the world, rice is heavily dependent on specific climate conditions, such as adequate rainfall, stable temperatures, and controlled water availability (Jagadish *et al.,* 2015; Prasad *et al.,* 2017). However, the increasing frequency of extreme weather events, rising temperatures, shifting rainfall patterns, and sea-level rise associated with global climate change are disrupting these essential conditions. It is estimated that nearly 51% of rice cultivation and production could decline over the next century as a result of global climate change (Firdaus *et al.,* 2020). Vietnam, as one of the world's largest rice producers and exporters (Maitah *et al.,* 2020; Yuen *et al.,* 2021), faces significant challenges from climate change, especially in its key rice -growing regions - the Mekong Delta and the Red River Delta. In recent years, Vietnam's climate is increasingly affected by the El Niño phenomenon and broader climate shifts, with 2023 marking the hottest year globally and recording the second-highest temperature in Vietnam's history. The highest recorded temperature in Vietnam, 44.2°C, occurred in the North Central region. Since early 2024, the country has experienced more frequent and severe natural disasters, including unusual cold spells, prolonged heatwaves, and increased salinity intrusion in the Mekong Delta. Projections by the United Nations Intergovernmental Panel on Climate Change and the World Bank suggest that a 1-meter rise in sea level could flood 0.3 to 0.5 million hectares of the Red River Delta and 1.5 to 2.0 million hectares of the Mekong Delta (Nguyen and Hens, 2019). During severe flood years up to 90% of the Mekong Delta could be submerged for four to five months, rendering large areas of rice fields unproductive due to flooding and salinisation. Additionally, the Asian Development Bank warns that a 1°C increase in temperature could result in a 10% decrease in rice productivity, posing a significant threat to national food security and affecting tens of millions of people.

The findings of the paper offer a wealth of insightful perspectives to explore and contemplate. In terms of temperature, the authors indicate a significant positive impact of maximum temperature on rice production across all models, with the effect being particularly strong for total and spring rice production. This suggests that, in the short term, rice production may benefit from warmer temperatures, especially during the growing seasons when heat accelerates crop growth and development (Hussain *et al.,* 2020). However, this positive correlation should be interpreted cautiously in the context of climate change. While moderate increases in temperature can enhance rice growth, extreme and prolonged heat waves pose serious risks to crop yields (Kaushal *et al.,* 2016; Sun *et al.,* 2019). Climate change is expected to bring more frequent and intense heatwaves, which can lead to heat stress, increased water evaporation, and reduced soil moisture (Li *et al.,* 2020; Yin *et al.,* 2022). These conditions may offset the current benefits of warmer temperatures. The spring rice season might experience greater vulnerability as higher temperatures coincide with the most critical growth phases such as flowering and grain-filling where extreme heat could reduce yield significantly (Raoufi and Soufizadeh, 2020; Shimono, 2011). Moreover, high temperatures can increase water demand, stressing irrigation systems and local water resources (Garrote, 2017; Wang *et al.,* 2016). In the long term, rising maximum temperatures could make certain provinces, especially those already experiencing warmer climates, less suitable for rice production without significant adaptation efforts. The results highlight the importance of developing heat-tolerant rice varieties and improving water management to cope with increasing heat risks.

The significant negative effect of minimum temperature on rice production, particularly for spring and total rice yields, highlights the detrimental impact of cooler night-time temperatures. This finding is supported by Lv *et al.* (2018); Peng *et al.* (2004); Shi *et al.* (2017); Yang *et al.* (2017) when they showed that high night-time temperature significantly decreases rice yields. Rice is highly sensitive to temperature fluctuations, and lower night-time temperatures can slow down physiological processes, delay crop maturation, and reduce overall productivity (Fahad *et al.,* 2019; Impa *et al.,* 2021). This negative effect is especially concerning in the context of climate change, where temperature variability is expected to increase, leading to more frequent occurrences of cold nights, even in traditionally warm regions (Freychet *et al.,* 2021; Saleem *et al.,* 2021). The spring rice crop appears to be more vulnerable to these cooler temperatures, as this season often coincides with transitional weather patterns where night temperatures can drop sharply. However, this conclusion contradicts perspective of Tan *et al.* (2021) who stated that while maximum temperature was negatively correlated with yield during the off-season, minimum temperature had a positive impact in both cropping seasons.

In addition, rainfall, sunshine, and humidity are three crucial factors that directly influence rice production. Each plays a vital role in the growth cycle of rice, a water-intensive crop that requires a delicate balance of environmental conditions to thrive. Rainfall is perhaps the most critical factor for rice production as rice is highly water-dependent (Bessah *et al.,* 2021). Rice fields need substantial amounts of water, especially during the initial growth stages, to maintain the flooded conditions essential for proper crop development. Sufficient and timely rainfall ensures that the rice paddies remain inundated, which helps control weeds and maintain soil fertility. However, both excessive and insufficient rainfall can harm rice production (Fu *et al.,* 2023; Rayamajhee *et al.,* 2021). Too much rain can lead to flooding, damaging crops, while too little can cause drought, stunting growth and reducing yields. This reliance on rainfall makes rice production particularly vulnerable to changing precipitation patterns caused by climate change. Maiti *et al.* (2024) indicated that both excessive and insufficient rainfall lead to reductions in rice yield of 33.7% and 19%, respectively. The optimal rainfall threshold across the country is identified as 1621 ± 34 mm; beyond this threshold, rice yield decreases by 6.4 kg per hectare for every additional 100 mm of rainfall.

Sunshine plays a crucial role in rice production, as it directly influences photosynthesis, the process by which rice plants convert light energy into chemical energy for growth and development (Firdaus *et al.,* 2020). The authors argue that sunshine has a positive impact on the production of rice, which aligns with the arguments of Panigrahy *et al.* (2020); Wei *et al.* (2023). Light deficiency alleviates the rice yield and quality. Adequate sunshine exposure is essential for optimal rice yields, as it affects plant height, leaf area, and grain filling (Zhou *et al.,* 2021). During critical growth stages, such as tillering and flowering, sufficient sunshine ensures the healthy development of panicles, leading to higher grain production (Song *et al.,* 2022). However, excessive sunshine, especially during heat waves, can increase plant stress, reduce water retention, and cause rice plants to wither (Semeraro *et al.,* 2023). Thus, balancing sunshine exposure with other factors, such as irrigation and shade management, is vital to ensure consistent yields, particularly in regions experiencing climate variability.

Moreover, high humidity levels can benefit rice during its growth phases by reducing evapotranspiration and helping the soil retain moisture (Fukai and Mitchell, 2022). However, excessive humidity can create favourable conditions for pests and diseases, such as fungal infections and insect infestations, which can significantly reduce yields (Naeem-Ullah *et al.,* 2020). The balance of humidity, particularly in tropical and subtropical regions where rice is commonly grown, is crucial. Managing humidity levels through proper field practices, pest control, and disease prevention measures becomes essential to ensure high productivity in rice farming.

Conclusions and policy implications

This study provides empirical evidence on the impact of climate change on rice production in Vietnam from 2002 to 2022, revealing significant relationships between climatic variables and rice yield outcomes. This study focuses on the impact of climate change on rice production in Vietnam, where there is distinct susceptibility to sea-level rise and salinity intrusion positions, rising temperatures, and extreme weather events. It is a unique case study while also offering valuable lessons for countries experiencing similar climatic challenges. The findings show that when maximum temperatures lie beyond the ideal range, rice yield may suffer. High temperatures can hasten crop development, shortening the growing period and lowering the time for photosynthesis, affecting the yields (Ding *et al.,* 2020). Because they lower seed set rate and grain weight, lower temperatures can limit crop output. Cold spells can also cause loss of winter-spring rice output (Su *et al.,* 2023). The proportion of rice spikelet fertility will be considerably lowered when daily mean temperatures are less than 22°C or average daily maximum temperatures throughout the flowering season are higher than 35°C (Ding *et al.,* 2020). Particularly in rainfed settings, rice farming depends on enough rainfall to provide the required water for plant development and growth (Amnuaylojaroen *et al.,* 2024). By 0.20% in the long run and by 0.19% in the short run, a 1% increase in precipitation will boost rice output (Chandio *et al.,* 2021). In mainland Southeast Asia, rice farming occurs in both the dry and wet seasons. While the rainy season runs from June to December, the dry season is marked by little precipitation. While increasing rainy weather spells could provide ideal conditions for rain-fed crops, they can also cause waterlogging and soil erosion (Amnuaylojaroen *et al.,* 2024). Changing the sowing dates will help to utilise the advantages of solar radiation and prevent too hot conditions (Ding *et al.,* 2020).

Based on these main findings, the following policy implications delineate a strategic framework aimed at strengthening the resilience of Vietnam's rice sector. Firstly, changing cropping patterns and introducing new rice varieties in place of traditional ones that are more sensitive to climate change might also help with adaptation (Aryal *et al.,* 2020). The government should work with research institutions to invest in breeding programs for varieties that can endure higher temperatures, increased salinity, and drought conditions. Besides, promoting sustainable agricultural practices is crucial for enhancing resilience to climate impacts (Usigbe *et al.,* 2024).

This can be done by means of the agro-ecological technique known as System of Rice Intensification (SRI), which enhances the management of water, soil, plants, and nutrients (Aryal *et al.,* 2020). Farmers should be trained in agroecological approaches that improve soil health, enhance biodiversity, and increase resilience to climate extremes (Bezner Kerr *et al.,* 2023). Policymakers should facilitate the dissemination of knowledge about these practices through agricultural extension services. This initiative should be supported by funding for agricultural research and development to ensure that new varieties are rapidly tested and distributed to farmers. The government should cooperate with agricultural research institutes in developing rice varieties that are resilient to climate change, expanding research cooperation models such as collaborating with the Vietnam Academy of Agricultural Sciences (VAAS) to promote research activities to select and breed rice varieties OM6677 and OM5451 that are highly resistant to current salinity and climate change conditions.

Secondly, adjusting planting dates is a common adaptation strategy that can be implemented with low cost using drought- and flood-resistant crop varieties (Ding *et al.,* 2020). Improving irrigation infrastructure is important to ensure a steady water supply for crops, particularly during dry seasons (Trinh *et al.,* 2021). Specially, the implementation of early warning systems for extreme weather events, such as floods, droughts, and typhoons, can significantly mitigate risks (Coughlan de Perez *et al.,* 2022; Neußner, 2021). These systems should provide real-time alerts to farmers and local communities, allowing them to take preventive measures.

Thirdly, the government should also limit cost barriers to rice production, implement appropriate tax policies, and provide preferential financing sources so that farmers have favourable conditions to improve current rice productivity. Infrastructure improvements and capacity building for smallholder farmers should be given top priority. The government also needs to strengthen its collaboration with international organisations and foreign funding sources to enhance cooperation in addressing climate change. Collaborating with organisations like the International Rice Research Institute (IRRI) and the Food and Agriculture Organisation (FAO) offers access to advanced research, best practices, and resources to enhance the nation's agricultural resilience (Byerlee and Lynam, 2020). A prime example of which is funding from the United States, which has provided Vietnam with $4.4 million to implement a project on proper fertiliser use. Climate change is coming and Vietnam is one of the most vulnerable countries in the world, and climate change is a top priority for the United States.

Lastly, the government should boost fundings for agricultural research on climate adaptation and resilience, allocating funding for developing and sharing innovative farming technologies to mitigate climate change impacts on paddy production (Haque *et al.,* 2024). Countries should engage with international research organisations and universities to enhance knowledge exchange and build capacity. Encouraging farmer cooperatives can boost capacity building and resource sharing among farmers. Cooperatives help farmers access training, technology, and financial resources, allowing them to adopt innovative practices together.

However, despite the thorough efforts undertaken, the study does have some limitations. A major one is the omission of socio-economic factors that could affect agricultural outcomes. Although the focus is on climatic variables like temperature, rainfall, and humidity, aspects such as farm size, access to irrigation, credit, and farmers' education are also critical to productivity. Larger farms often have greater access to resources and technology, while smallholders may face challenges in adapting. Future research should incorporate these socio-economic factors to gain a more comprehensive understanding of how climate change interacts with broader socio-economic conditions. Another limitation is the reliance on provincial-level data, which may miss important micro-level variations. Provincial averages reveal general trends but overlook local differences, such as agricultural practices, resource availability, and vulnerability to climate impacts. Future studies should use farm-level or household data to better capture these localised differences, providing insights that lead to more targeted policy recommendations.

Despite these constraints, the study provides valuable insights into the broad impacts of climate change on rice production. These findings can still help shape national and provincial policies, particularly in developing strategies to address climate risks. Future research should expand its scope to include more detailed data and socio-economic factors, improving our understanding of resilience and supporting the development of more inclusive and effective climate adaptation policies.

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MARKET ANALYSIS

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Economic impacts of banning the enriched cage housing system in Hungarian table egg production

This study aims to examine the economic impacts of phasing out enriched cages in Hungarian table egg production. An online questionnaire survey was conducted among 42 enriched cage egg producers and in-depth interviews were carried out with barn and aviary egg producers, as well as a company specialised in designing and implementing housing systems for laying hens, using economic and physical efficiency data for the year 2021 from egg producers. Economic situation was examined via a simulation model, which was based on on deterministic principles. The results indicate that aviary and barn housing systems exhibit lower physical efficiency and weaker economic indicators when compared to the enriched cage housing system. Aviaries and barns showed reduced egg production per hen (-7% and -12%, respectively), increased feed conversion ratio (FCR) (+17% and +24%), reduced labour efficiency (-40% in both cases), and increased mortality rate (+2.49 and +3.31 percentage points). Key determinants of unit gross margin alterations were found to be egg production per hen, the share of class 'A' eggs, FCR, and pullet acquisition cost. Aviary housing systems proved as profitable as enriched cage systems in terms of gross margin per egg, whereas barn housing systems were unprofitable based on 2021 data. However, those barn eggs producers who sell directly to consumers can still be profitable. The investment payback periods of enriched cage (7 years) and aviary (10 years) housing system differ. In conclusion, aviaries and barns could not outperform the enriched cage housing system in economic terms.

Keywords: laying hen, aviary, barn, enriched cage, gross margin, investment cost

JEL classifications: Q12, Q13.

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Introduction

In 2021, the EU-27 produced almost 6.5 million tonnes table eggs, an increase of 15% compared to 2012. Despite a 14% growth in EU egg consumption (reaching 6.2 million tonnes), the self-sufficiency level remained notably stable over the past decade, ranging between 103-106%. France (14%), Germany (14%), Spain (12%), Italy (12%), the Netherlands (10 %), and Poland (9%) were the leading egg-producing countries in the European Union, accounting for approximately 71% of the community's egg production (including hatching eggs) in 2021 (EC, 2023a).

In the European Union, including Hungary, the cage housing system of laying hens underwent several changes between 1999 and 2012. The minimum cage area of 450 cm^2 had to be changed to 550 cm^2 in unenriched cages from 2003 (20/2002 (III.14.) FVM Regulation). However, only a minimum cage area of 750 cm^2 was allowed in enriched cages from 2012 (Council Directive 1999/74/EC). In addition to the perch, a perching area of 15 cm per bird, a minimum of one laying nest and scratching area with litter had to be provided. Only the slope of the floor (14%) and the number of drinkers per cage (min. 2 pieces per cage) did not change between 1999 and 2012 (Marlok and Kovácsné Gaál, 2008). The latest requirement is still in force.

In Hungary the latest change of cage housing system in 2012 resulted in an increase in the unit cost of eggs produced for each farming method. Compared to conventional cages, the unit cost of eggs produced in barn housing systems has increased by 20%, free-range housing system by 50% and organic housing system by 100% (Alicki, 2012). Since Hungarian consumers lack sufficient information about various production housing systems – a situation similar to that highlighted by the study by Molnár and Szőllősi (2015) – their purchasing decisions are not primarily based on this factor. Their preferences include undamaged eggs, shelf life, and food safety (Szőllősi *et al*., 2022).

Based on 2021 data from the National Food Chain Safety Office (NFCSO, 2021), 83.9% of layer spaces in Hungary were occupied by hens in enriched cage system. Barn and aviary housing systems make up 15.2% while free-range and organic housing systems represent only 0.5% and 0.4% respectively (Csorbai *et al*., 2022).

At the EU level, cage systems make up 44.9% of egg production, while aviary and barn housing systems account for 35.6%, free-range housing systems represent 12.8%, and organic housing systems make up 6.6% in 2021 (EC, 2023a). The proportion of cage systems decreased by around 5% in 2022. Among the major egg-producing countries (France, Germany, Spain, Italy, the Netherlands, and Poland), enriched cage systems are still predominantly used in Poland (71.8%) and Spain (68.6%) (EC, 2023b). Therefore, the removal of cage systems would put many egg-producing businesses in the EU at risk.

The 'End the Cage Age' civil initiative (2021) of the European Union strives to produce animal products in housing systems devoid of cages. Recently, Potori *et al.* (2023) investigated the socio-economic implications of abolishing use of conventional farrowing crates in the pig sector. The Hungarian pig production would fall by 23.6% in case of immediate termination scenario and by 8.4% in the case of a phase-out until 2035. This banning would affect both domestic demand and the EU's trade negatively.

Since the European Commission addressed table egg production in their announcement, conducting an impact assessment is crucial. Majewski *et al.* (2024) found that an immediate ban would cause a significant drop in the EU's egg production (from 6.9 million tonnes to 5.6 million tonnes). The additional investment cost of the alternative housing systems would range from 2 to 3.2 billion EUR based on the different scenarios.

As enriched cage is the most common housing system of the Hungarian table egg production (85%) and no studies in Hungary have examined the impact of banning of the enriched cage housing system, our study intends to examine the economic alterations which are likely to take place upon the phase-out of cage in Hungarian table egg production.

Literature review

In the literature, studies mainly focus on animal welfare, production features, parameters, cost-income analysis and investment costs of different housing systems. For instance, a report conceded that a significantly higher number of bacterial (mainly colibacillosis) or parasitic diseases (coccidiosis and red mite), and cannibalism occur in laying hens kept in barn housing systems or in free-range housing systems than in hens kept in cages. The occurrence of viral diseases was significantly higher in indoor barn housing system than in cages (Fossum *et al.,* 2009). Keel bone damage is also a frequent problem of commercially raised laying hens. In Greek farms this type of injury was observed mainly in the free-range system (50 %), followed by enriched cages (24 %) and floor system (7 %) (Dedousi *et al*., 2020). According to Campbell *et al*. (2021) there is a much higher occurrence of diseases, exposure to predators, and heat stress in free-range housing system, however, it has the advantages of foraging and better plumage.

Table 1: The changes in physical efficiency indicators of non-cage housing systems compared to the cage system.

Indicators	Enriched cage = 100%	Barn/ Aviary	Free-range	Organic
Laying period (laying days)	100	100	94	94
Egg production (hen housed)	100	98	91	91
Feed consumption (g/day/hen)	100	105	109	110
Egg production per hen housed (kg)	100	97	89	89
Number of hens per worker	100	57	36	19

Source: own compilation based on van Horne and Bondt (2023)

Table 1 presents that moving from enriched cage systems to non-cage housing systems (barn, aviary, free-range and organic) leads to a deterioration of physical efficiency indicators (van Horne and Bondt, 2023).

In the European Union, the production cost of enriched caged eggs is approximately 16-27% higher compared to some third countries (USA, Ukraine, India, Argentina). This is due to the facts that, on one hand, US, Ukrainian and Argentinian farmers experience 5-19% lower feed costs, and on the other hand, they have 18-24% lower pullet costs compared to European farmers. The only exception was India, where higher feed costs (+6%) was observed compared to the EU average in 2021 (van Horne and Bondt, 2023). However, all these factors create a competitive disadvantage for the EU producers.

According to calculations by van Horne and Bondt (2023), the per egg costs of egg production are 14% higher in aviary/barn housing systems, 32% higher, in free-range housing systems and 110% higher in organic housing systems compared to the enriched cage housing system based on data from 2021. A previous study by van Horne (2019) found that aviary and barn together have an average 17% higher egg production costs than in enriched cage systems.

The study by van Horne and Bondt (2023) compared the production costs of barn and free-range eggs to the cage housing system in several EU countries, the largest increase in production costs for eggs produced in the barn housing system was observed in France (+27%), while the smallest increase was in Hungary (+18%). Where eggs were produced in free-range housing systems, the most significant increase in production costs compared to the cage housing system was in the Netherlands and France (+39%) in 2021.

Molnár and Szőllősi (2020) stated that economically (also in social and environmental aspect), non-cage housing systems are not the most favourable for production conditions. According to a previous study (Szőllősi *et al.,* 2019), in Hungary, the unit cost per egg in barn housing system was approximately 39% higher compared to the cage housing system, referring to the average of the period from 2012 to 2015. However, in relation to this, a subsequent Hungarian case study based on data from the years 2016-2017 (Erdős *et al.,* 2019) revealed that the farm using the barn housing system managed to produce one egg at about 30% higher production costs, while the farm applying aviary housing systems had approximately 33% higher production costs compared to the cage housing system.

On a per hen basis in the Hungarian enriched cage housing system had one of the lowest production costs and one of the highest gross margins (Erdős *et al.,* 2019; Szőllősi *et al.,* 2019). However, a similar gross margin can also be achieved by the farm applying barn housing system, if sales are made directly to consumers (Erdős *et al.,* 2019).

During the transition to cage-free housing systems investment costs also change. Based on van Horne and Bondt (2023)'s study, while the investment costs for barn,

Table 2: The evolution of investment costs in different housing systems

Denomination	Enriched cage	Barn/ Aviary	Free-range	Organic
Housing (euro per hen housed)	8.50	13.53	13.43	20.31
Inventory (euro per hen housed)	16.80	17.50	17.50	28.00
Total (euro per hen housed)	25.30	31.03	30.93	48.31
Total (Enriched cage =100%)	100	123	123	191

Source: own compilation based on van Horne and Bondt (2023)

aviary, and free-range housing systems are 23% higher, the investment costs for the organic housing system surpass the cage housing system by 91% (Table 2).

Methodology

In collaboration with the Hungarian Poultry Product Board (HPPB), an online questionnaire survey was carried out in 2022 based on 2021 data among 42 producers using enriched cage systems, representing around half of the average annual population of hens in enriched cages. Furthermore, in-depth interviews were conducted with producers of barn and aviary eggs, as well as a consultancy firm specialising in housing systems' design and implementation. Based on the chosen technology-dependent physical and economic indicators, a deterministic simulation model was developed to quantify the effects of parameters (egg production per hen, price of class "A" eggs, share of class "A" eggs, mortality rate, permanent workers, feed conversion ratio, price of pullet, stocking density). The model's primary outputs were the indicators characterising the cost and income situation of producers using enriched cages, barns, or aviaries. To prioritise among the available technologies, the marginal cost of production was listed per egg per unit area and per hen, as these are widely accepted measures. The following main cost items were identified in our analysis:

- *Pullet cost:* The difference between the purchase value of the pullets and the value of the culled breeding stock, adjusted for the length of the production cycle.
- *Feed cost:* Determined by the market price of the compound feedstuffs. In cases of in-house production, the opportunity cost was also considered alongside the overhead costs.
- *Variable labour costs:* Egg production typically requires a significant proportion of man-hours, mainly seasonal, which was classified as a variable cost. Related taxes and social contributions were also included.
- *Other variable costs:* All additional variable costs related to egg production (e.g., veterinary costs, carcass removal costs, energy costs, packaging material costs).
- *Permanent labour costs:* The cost of labour that consistently supervises the layer stock. Related taxes and social contributions were also included.
- *Other fixed costs:* All fixed costs not previously listed, such as building maintenance costs.

Depreciation, general costs, and the cost of capital were not considered in estimating incomes.

Calculations were based on the survey questionnaire to typify the three main types of laying hen housing technologies in Hungary in 2021. Based on in-depth interviews and van Horne (2019) the stocking density was estimated to be 26 hens/m^2 for enriched cages, 17 hens/m^2 for aviaries, and 9 hens/m^2 for barns. The parameters for enriched cages served as the benchmark against which the alternative technologies were evaluated in the model. Indices adopted in the literature included various physical and economic parameters, such as egg production per hen, share of class "A" eggs, price of class "A" eggs, mortality rate, permanent labour cost, energy cost, feed consumption, price of pullets, and stocking density.

Additionally, the economic efficiency parameters of egg production were determined per egg, per hen and per square metre for the enriched cage, aviary, and barn housing systems. In-depth interviews and literature sources (Table 3) were used to establish real investment costs. For the calculation of investment costs, a 20-year fixed-term government bond was used as the reference interest rate (3.62%) for 2021. A useful life of 20 years was assumed for the investment. For the analysis of the return on investment, the most important indicators (NPV and IRR) were used (Szűcs and Szőllősi, 2008). When calculating operating cash flows, future increase in egg prices was anticipated and production costs based on past trends. To express the results in euros, the official average exchange rate for 2021 (358.52 HUF/EUR) was used.

Investment alternatives were evaluated under three different scenarios that varied in terms of support levels (equity – using only own equity; 30% or 50% investment support intensity). Based on our assessment, the barn technology was excluded as it generates no income without subsidies. We calculated the cumulative net present value and the internal rate of return for each year within a 20-year useful life.

A limitation of the study is that the results are only relevant for the year 2021. However, this year is considered more transparent in the sense that it rejects the extreme economic and natural conditions in 2022 and 2023. From 2022 onwards, geopolitical factors, extreme drought, price volatility would have an impact on the cost-income situation and investment economics calculations.

Table 3: Range of sources used to derive the indices for each factor.

Indicators	Index – Aviary (Enriched cage=1)	Sources	Index – Barn (Enriched cage=1)	Sources
Egg production per hen	0.93	in-depth interviews and Bouzidi (2021)	0.88	in-depth interviews
Price of Class “A” egg	1.23	FADN (2020)	1.23	FADN (2020)
Share of Class “A” egg	0.98	in-depth interviews	0.96	in-depth interviews
Mortality rate	1.60	in-depth interviews	1.80	in-depth interviews
Permanent worker	1.66	in-depth interviews; Bouzidi (2021), van Horne and Bondt (2017); van Horne (2019)	1.75	in-depth interviews; Bouzidi (2021), van Horne and Bondt (2017); van Horne (2019)
Feed conversion ratio (FCR)	1.09	in-depth interviews; Bouzidi (2021), van Horne and Bondt (2017); van Horne (2019); Szőllősi (2013) cit. Castello, (2011)	1.09	in-depth interviews; Bouzidi (2021), van Horne and Bondt (2017); van Horne (2019); Szőllősi (2013) cit. Castello, (2011)
Price of pullet	1.13	in-depth interviews, van Horne and Bondt (2017); van Horne (2019);	1.13	in-depth interviews; van Horne and Bondt (2017); van Horne (2019);
Energy cost	0.90	in-depth interviews, Bouzidi (2021), van Horne (2019)	0.90	in-depth interviews, Bouzidi (2021), van Horne (2019)
Stocking density	0.67	in-depth interviews, van Horne (2019)	0.33	in-depth interviews, van Horne (2019)
Investment cost	0.80	in-depth interviews, van Horne (2019)	0.40	in-depth interviews, van Horne (2019); Szőllősi (2013) cit. Castello, (2011)

Source: own compilation

Results and Discussion

Based on the results of the questionnaire survey, in enriched case housing system, the average flock size was around 57 000 birds in 2021, with an extremely low relative standard deviation (0.70%). While the smallest farm had around 600 birds, the largest company had almost 500 000 laying hens in the same year. The average number of eggs produced per hen was 291.

Based on the respondents, the average production cycle was 59 weeks. The annual mortality rate was 4.16%, with a high relative standard deviation (31.18%). The average daily feed consumption per hen was 122.4 grams, almost identical to the median value (122.5 grams). The feed conversion ratio (FCR) recorded an average of 2.5 kg/kg, with a low relative standard deviation (0.35%). The number of laying hens per full-time worker was approximately 8,000 in the examined year (Table 4).

Table 4: Descriptive statistical analysis of the most important parameters related to enriched cage eggs production (n=42)

Indicators	Mean	Median	Relative standard deviation
Average number of hens (birds)	57 137	15 703	0.70
Egg production (eggs/average number of hens per year)	291	300	0.64
Average share of class “A” eggs (%)	93.51	95.00	5.20
Length of production period (weeks)	59	61	2.64
Average annual mortality (%)	4.16	4.00	31.18
Average feed consumption (g/hen per day)	122.41	122.50	1.45
FCR (kg/kg)	2.48	2.49	14.32
Hens per permanent worker	7 992	3 553	0.90

Source: own calculations

The results of the online questionnaire survey and the experience of the in-depth interviews

If enriched cages were banned, more than half (52.4%) of the egg producers surveyed in Hungary would stop their production. A further quarter (26.2%) would switch to aviary housing system, almost one-fifth (19.0%) would diversify, and the remainder (2.4%) would choose barn, free-range, or organic housing systems.

During the in-depth interviews, a range of risk factors were identified that require thorough consideration before the enriched cage housing system can be phased out:

- In buildings currently using enriched cage housing systems, transitioning to aviary housing system may often be unfeasible, requiring greenfield investments.
- Direct monitoring of animals and increased dust levels could negatively affect working conditions, leading to a reduction in labour supply.

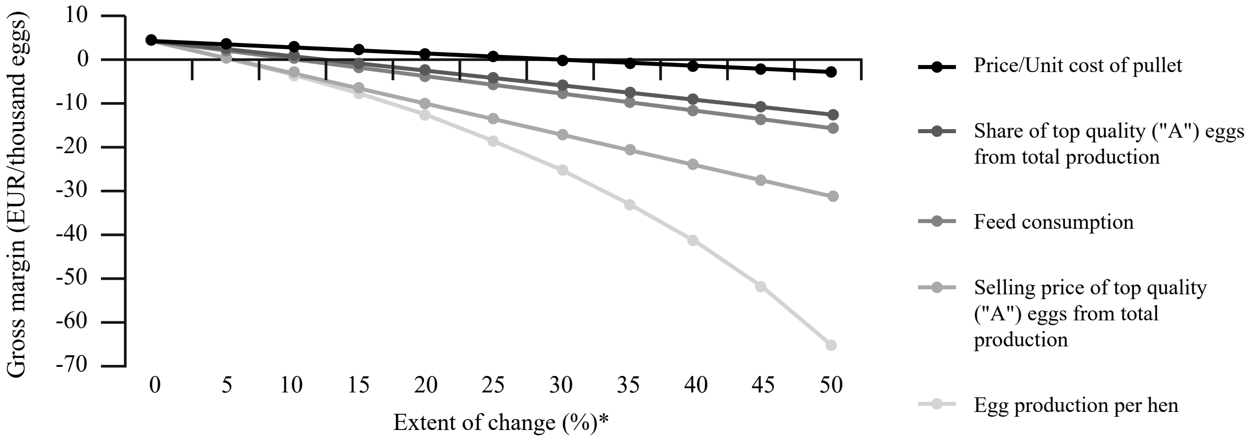

Figure 1: Sensitivity analysis of the most important factors on the gross margin/farm income of egg production

* Direction of change based on Table 5: Egg production per hen: (–), Selling price of class "A" eggs: (–), Feed consumption: (+), Share of class "A" eggs: (–), Price/Unit cost of pullet: (+)
Source: own calculations

- Sufficient supplies of pullets are crucial when shifting to alternative housing systems (barn and aviary).
- In cage-free rearing, the absence of individual data collection, aggressive bird isolation, and safeguarding the health of birds and workers will be challenging.

These challenges not only affect the breeding process but also have indirect negative consequences for pullet rearers. The deterministic model is allowed to quantify the effect of a unit change of any of the input parameters on the per egg income using sensitivity analysis. For example, a 1% decrease in the producer price of class "A" eggs, the gross margin changed from 4.83 EUR/thousand eggs to 4.11 EUR/thousand eggs. This reduction decreased profitability by 0.07 eurocents per egg (-14.95%). Accordingly, the technology-dependent factors that have the most significant effect on the per egg profitability were the annual egg production per laying hen, followed by the selling price of class "A" (top quality) eggs, the daily feed consumption per hen, the proportion of class "A" eggs and the value of pullet put into production. Figure 1 illustrates the effect of any departure on each of these items.

A 1% decrease in the number of eggs per hen, the gross margin changed from 4.83 EUR/thousand eggs to 4.13 EUR/thousand eggs. This reduction decreased profitability by 0.07 eurocents per egg (-14.63%). The performance of the layers in alternative systems could reach the standard in cage systems, however the proportion of litter eggs is higher. Some of the eggs laid outside the nest break, which ultimately reduces the marketable egg production per hen. Our data collection confirmed the literature's assumptions (Bouzidi (2021); van Horne (2019)), namely: the number of eggs per hen was typically lower in the aviary (-7%) and barn systems (-12%) with respect to the enriched cages. Thus, the projected income per egg in the alternative systems decreased by 0.5 and 0.9 eurocents, respectively.

The third significant factor influencing profitability is feed consumption. As a result of 1% increase in daily feed consumption per hen, the gross margin changed from 4.83 EUR/thousand eggs to 4.42 EUR/thousand eggs. This reduction decreased profitability by 0.04 eurocent per egg (-8.47%). There was a consensus among the interviewees that the chosen technology has ultimately a significant bearing on feed consumption. More movement and the associated increase in energy demand leads to higher feed consumption. In the two investigated alternative technologies, feed consumption increased to a similar extent compared to the enriched cage technology (8.66% for the aviary and 8.97% for barn), which led to a loss of 0.4 eurocents per egg.

In 2021 the selling price of class "B" eggs (for industrial use) was roughly half of class "A" eggs (top quality ready for direct human consumption). The average selling price of the eggs directly depended on the proportion of class "A" and "B" eggs, which therefore had a considerable effect on the overall profitability. For example, a 1% reduction in the proportion of class "A" egg led to a change in the gross margin from 4.83 EUR/thousand eggs to 4.48 EUR/thousand eggs. This decline in the ratio caused 0.04 eurocent per egg loss in gross margin (-7.27%). According to our data, the proportion of class "A" eggs was on average 93.5% using the enriched cage technology. This ratio was 2.3% points lower in aviaries and 3.7% points lower in barns. The gross margin decreased by 0.09 and 0.14 eurocents per egg, accordingly.

As the purchase price of pullets or the internal cost of in-house pullet production increased by 1%, the gross margin changed from 4.83 EUR/thousand eggs to 4.68 EUR/thousand eggs. This reduction caused 0.02 eurocent loss per egg in gross margin (-3.15%). The ban on enriched cage farming would also affect the production costs of raising pullets, since the technology used for their rearing needs to align with the housing systems of keeping layers. A particularly relevant problem is that alternative technologies do not allow individual data collection on the breeding stock, thereby impairing the pace and efficiency of genetic selection. This could have ripple effect across the entire poultry sector. In accordance with the literature, we assumed a moderate, 13.14% increase in the price of pullets, which translates to a loss of 0.2 eurocents per egg.

Labour input is an issue that deserves special attention when evaluating the competitiveness of laying hen farming. Based on our results, a full-time staff member took care of an enriched cage operation of the size of 8,110 animals, while this number dropped to 4,874 in the case of aviary and 4,636 in the case of barn technology. Given the 66% to 75% increase in labour costs, the gross margin per egg would be 0.3 to 0.4 eurocents lower in the alternative systems. Therefore, the rise in time commitment resulting from technological changes had a negative impact on profitability comparable to the impact of increased feed consumption.

In the alternative systems, issues such aggression, parasitic transmission, or suffocation from overcrowding are more common, making them difficult to manage even with adequate care and expertise. A rise in the mortality rate impacts various cost factors. It decreases the operation's throughput, increases the cost of carcass removal, and decreases the income from the sale of cull hens. The 2.49-3.31 percentage points higher mortality rate eroded profitss by 0.04-0.06 eurocents on each egg.

The physical efficiency indicators of table egg production deteriorate significantly when moving from enriched cage housing systems to aviary and barn housing systems (Table 5). The egg production per hen is 270 in the aviary housing system and 256 in the barn housing system. Consequently, the egg yield per unit is 7% and 12% lower in the alternative systems (aviary and barn). The mortality rate is 2.49 to 3.31 percentage points higher in the non-cage housing systems. While the daily feed intake is approximately 8.1 to 8.7% higher, the FCR is 17% to 24% higher in the alternative housing systems (barn and aviary) compared to the enriched cage housing system. There is a significant difference in stocking density. There are 35% fewer birds in the aviary system and 65% fewer in the barn housing system compared to the enriched cage housing system.

The production cost per hen is 13% to 15% higher in the alternative housing systems (aviary and barn) compared to the enriched cage housing system (Table 6). In comparison, according to Szőllősi *et al.* (2019), the production cost was only 2% higher for the barn housing system (averaged over the years 2012-2015). However, Erdős *et al.* (2019) observed slightly higher differences. The production costs per hen in the barn housing systems were 7% higher. On the other hand, this difference was 39% in the case of the aviary and cage housing systems. According to van Horne and Bondt's (2023) calculation the difference of the production cost (without general costs) was 10% between the enriched cage housing system and alternative housing systems (aviary and barn).

The largest cost component is feed (55-58%), followed by pullets (20-21%), and then labour costs (12-15%). Feed and pullet costs are higher by 9% and 17% in the aviary and barn housing systems. In comparison, there are more significant differences in permanent labour costs (+66-75%) and other fixed costs (+57-191%) in the non-cage housing systems.

Despite the fact that, in the aviary and barn housing systems, there is a higher producer price but a lower egg production per hen, the production value is 12% and 5% higher in the case of aviary and barn housing systems compared to the enriched cage housing systems. However, higher production costs reduce profitability. Consequently, in the case of aviaries, a 9% lower unit gross margin is achieved compared to the enriched cage housing system. In contrast, based on our calculations, the barn housing system results in a loss of production. However, those producers who sell directly to consumers can still be profitable. According to Szőllősi *et al.* (2019) the enriched cage housing system is the best farming method for large scale producers (due to the economies of scale achieved); however, barn and aviary housing systems are more suitable for smaller scale table egg producers.

While the aviary hosuing system achieves a 1.34 percentage points lower cost-profitability ratio (5.58%), this difference is more pronounced in the barn hosuing system, where the cost-profitability ratio (-2.34%) is 9.26 percentage points lower than in the enriched cage housing system.

The per-egg cost and income data are outlined in Table 7. The production cost per egg is 22% higher in the aviary housing system and 31% greater in the barn housing system compared to the enriched cage housing system. In contrast, the

Table 5: The change of the most important parameters in different housing systems, 2021.

Production indicators	Unit of measurement	Enriched cage	Aviary	Barn
Egg production	eggs/average number of hen per year	291	270	256
Mortality rate	%	4.16	6.65	7.47
Feed utilisation	g/hen per day	122.00	132.56	132.95
Feed conversion ratio (FCR)	kg feed/kg egg	2.46	2.88	3.05
Hens per permanent worker	hens/worker	8 110	4 874	4 636
Stocking density	hen/m^2	25.50	16.53	8.98

Source: own calculations

Table 6: Cost and gross margin per hen in different housing systems, 2021.

Denomination	Enriched cage	Aviary	Barn
	EUR/hen	EUR/hen	EUR/hen
Pullet cost	4.10	4.78	4.82
Feed cost	11.92	12.95	12.99
Variable labour cost	0.93	0.93	0.93
Other variable cost	1.84	1.82	1.83
Fix labour cost	1.47	2.45	2.58
Other fix cost	0.11	0.17	0.32
Total direct cost	20.38	23.11	23.47
Production value	21.79	24.40	22.91
Gross margin	1.41	1.29	-0.55

Source: own calculations

Table 7: Cost and gross margin per egg in different housing systems, 2021.

Denomination	Enriched cage	Aviary	Barn
	eurocent/egg	eurocent/egg	eurocent/egg
Pullet cost	1.41	1.77	1.88
Feed cost	4.10	4.79	5.07
Variable labour cost	0.32	0.35	0.36
Other variable cost	0.63	0.67	0.72
Fix labour cost	0.51	0.91	1.01
Other fix cost	0.04	0.06	0.12
Total direct cost	7.00	8.55	9.16
Production value	7.49	9.02	8.94
Gross margin	0.48	0.48	-0.22

Source: own calculations

Table 8: Investment profitability in different housing systems.

Denomination	Indicators	Enriched cage	Aviary
Own equity	NPV (EUR/m^2)	343.95	83.78
	IRR (%)	4.54%	1.53%
30% investment support intensity	NPV (EUR/m^2)	525.10	227.32
	IRR (%)	8.87%	5.30%
50% investment support intensity	NPV (EUR/m^2)	645.87	323.01
	IRR (%)	13.82%	9.50%

Source: own calculations

production value is 21% larger in the aviary housing system and 20% greater in the barn housing system compared to the enriched cage housing system. In terms of gross margin per egg, the aviary housing system approaches the profitability of the cage housing system, while the barn housing system shows losses.

Our research was completed with an investment profitability analysis, based on the production cost and production value per square metre. Comparing the different housing systems, the production costs per square metre in the enriched cage housing system are 36% and 147% higher than the production costs for the alternative housing systems (aviary and barn). In the enriched cage housing system, due to the significantly larger stocking density per unit area, a much higher amount can be achieved, with an increase of 69%.

The investment cost of the enriched cage housing system is the highest (604 EUR/m^2), exceeding the investment profitability analysis of the aviary housing system by 26%, and that of the barn housing system by 149%. In the investment cost analysis, we considered different scenarios for both the enriched cage and aviary housing systems, assuming a useful life of 20 years (Table 8). The net present value for each case is positive for both the enriched cage and aviary housing systems. In one case (own equity), the internal rate of return is lower than the applied discount rate applied, suggesting that risk-free investments (3.62%) could be more favourable. The payback period varies between 7 and 14 years for the enriched cage housing system investment, and between 10 and 18 years for the aviary housing system investment, depending on the level of support.

Comparing the investment analyses of enriched cage and aviary housing system at 50% subsidy intensity, the enriched cage housing system pays for itself in 7 years, while the aviary housing system pays for itself in 10 years. The net present value realised with the enriched cage housing system investment is twice as large as that of the aviary housing system (Figure 2).

Conclusions

The study analysed the economic impacts of phasing out the enriched cage housing system in Hungary. Overall, the aviary and barn housing systems showed lower physical effi-

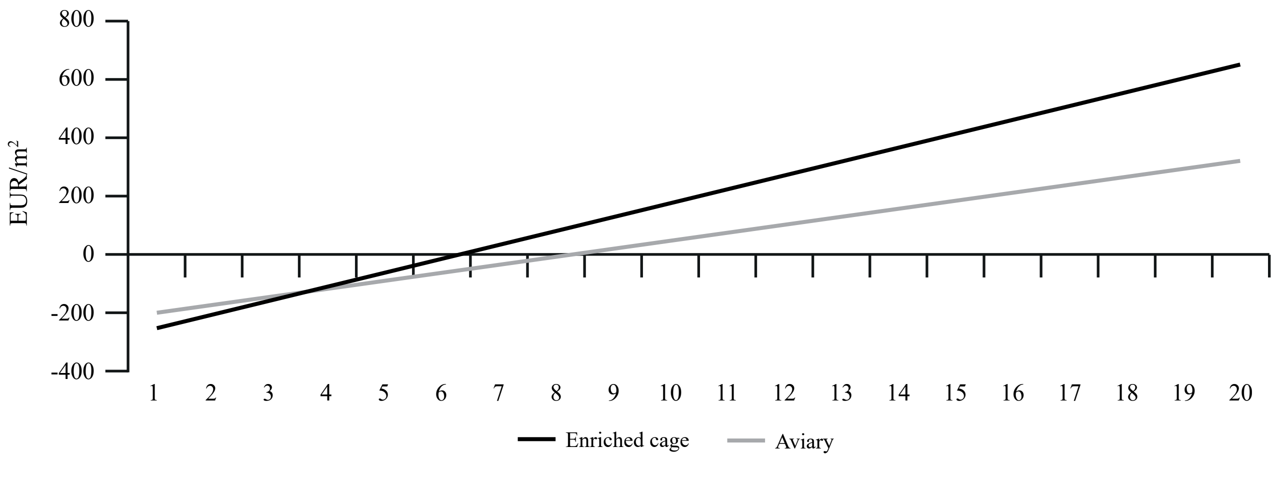

Figure 2: Cumulative net present value in enriched cage and aviary housing system (50% investment support intensity)

Source: own calculations

ciency and economic indicators compared to the enriched cage housing system. The egg production per hen was lower by 7% in aviary and by 12% in barn housing systems. The FCR was higher by 17% (aviary) and 24% (barn). Labour efficiency (hens per permanent worker) fell by 40% in both cases. The unit gross margin per hen was lower by 9% in aviaries compared to the enriched cage housing system. In barn housing system the production was not profitable. However, by selling directly to consumers egg production still can be profitable in barn housing system. The investment payback period was 7 years in the enriched cage housing system and 10 years in the aviaries housing system (with a 50% subsidy intensity).

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