**Using Mathematical Optimization for the Transition to Sustainable and Circular Agriculture**

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Abstract

This paper introduces a novel index, the Agricultural Circularity and Sustainability (ACS) index, for evaluating the circularity and sustainability of agriculture. Implemented as a multi-criteria objective function within a MILP model of the food supply chain, the ACS index optimizes various measures for transition of agriculture to circular and sustainable performance. Inspired by the circularity index developed by Baratsas et al. (2022) for companies, the ACS index is tailored for agricultural applications. It assesses measures such as reducing artificial fertilizer use, food waste generation, and a change of dietary habits, while promoting organic farming, enhancing food production efficiency, and balancing the import and export of animal-origin food products. A case study for Slovenia demonstrates that implementing these measures would more than double the overall ACS index. The optimization model, equipped with the new ACS index, serves as a unique tool for systematically planning and implementing long-term measures to transform national agriculture towards a sustainable and circular economy.

**Keywords**: circular, sustainable, agriculture, food supply chain, MILP optimization

* 1. Introduction

Food production and the agricultural sector are of paramount strategic importance for every country and the world as a whole, especially in light of a growing population and the increasing rate of climate change. The current state of agriculture, however, raises significant environmental and social concerns. Agriculture is a major contributor to climate change, accounting for approximately 10.3% of the EU's greenhouse gas (GHG) emissions (European Commission, 2020). Overuse of fertilizers and pesticides pollutes soils, watercourses, and groundwater. Excessive soil cultivation leads to erosion and fertility loss. Another issue in the food sector is the excessive consumption of animal protein, resulting in vast areas of arable land being used for animal feed, and substantial food loss and waste (Circle Economy, 2020). Agriculture remains predominantly linear, necessitating a shift towards circularity to mitigate its environmental impact. A unified metric for quantitatively assessing agricultural circularity is yet to be adopted. Despite the absence of a standardized metric, the theoretical principles and some indicators for measuring agricultural circularity are established (Velasco-Muñoz et al., 2021). Circular agriculture adheres to the principle of maximizing resource efficiency, utilizing both raw materials and waste effectively (Circle Economy, 2020). This can be achieved through various measures, such as localizing livestock, feed and food production, minimizing edible food waste and GHG emissions, optimizing bio-waste utilization within the chain (e.g., for animal feed) or bio-based products and fuels production (Circle Economy, 2020). Agricultural practices must incorporate the principles of regeneration, recycling, and minimization (Dagevos et al., 2021), such as composting and anaerobic systems that reduce waste generation. Advanced production techniques also play an important role, including conservation agriculture, precision agriculture utilizing drones and sensors, digitalization, and geographically adapted food production to address the ongoing negative impacts of global warming (Ali Chandio, 2023). The intricate nature of the food supply chain necessitates a systemic approach to developing effective measures that promote circular and sustainable agriculture. In our previous work, a mixed-integer linear programming (MILP) model for optimizing arable land allocation to major food and feed crops was developed (Drofenik et al., 2023). This model helped identify key conflicts and synergies within the food supply chain. The aim of this study is to extend previous work by: a) developing a novel multi-criteria metric to maximize circularity and sustainability of agriculture and b) assessing the impact of different measures on the transition of agriculture to a circular economy.

* 1. Methodology
     1. Basic mathematical model

The basis of the present study is the MILP model by Drofenik et al. (2023), encompassing primary food production, processing, distribution, consumption, and waste management. This model optimizes distribution of crop cultivation areas, crop yields, agricultural production types, livestock numbers, and various indicators such as GHG emissions, fertilizer consumption, self-sufficiency rates, economic potential etc. The model's implementation was validated using a case study on the optimization of the entire food chain in Slovenia. This work identified the crucial trade-offs and clearly demonstrated that food production decisions must prioritize food security and environmental protection beyond mere economic considerations.

* + 1. Agriculture circularity and sustainability (ACS) index

To drive circular and sustainable solutions within the food supply chain, a novel Agricultural Circularity and Sustainability (ACS) index is developed and integrated into the mathematical model as a multi-objective function. Inspired by the MICRON system (Baratsas et al., 2022) initially designed for the industrial sector, the ACS index incorporates the three pillars of sustainable development (economy, society, and environment) as primary categories. Additionally, food losses and waste (FLW) were included as a separate category due to its significance in achieving the United Nations' (2015) goals and its detrimental impact on all sustainability aspects.

Table 1 shows the indicators of the principal categories Economy, Society, Environment and FLW. Economy indicators (econ) are defined on the production side as annual production costs and revenues per capita. Indicators for the Society category (soc) are defined as modified self-sufficiency rates for Slovenia's seven most consumed food groups. The self-sufficiency rate for each food group (*SSi*) is reduced by the export-to-consumption ratio (Eq. 1), thus reflecting the proportion of domestically produced food that is available for local consumption. This modified indicator promotes local food production and thus corresponds to the objectives of this main category.

|  |  |
| --- | --- |
|  | (1) |

The first three indicators of Environment principal category (env), focusing on GHG emissions, mineral fertilizers, and organic farming, align with the objectives of the Farm to Fork Strategy (European Commission, 2020). Our previous research (Drofenik et al., 2023) revealed that minimizing agriculture's environmental impact could lead to increased food imports, potentially causing carbon leakage. Therefore, indicators for annual food and feed imports (env4) and exports (env5) were incorporated to mitigate cross-border environmental impact transfers. The indicators of the category Food loss and waste (FLW) are the amount of total and edible food waste. Edible food waste is given a special indicator as it can be directly influenced by encouraging residents to handle food more responsibly, while the amount of inedible food waste is very difficult to reduce.

Table 1: Indicators of principal categories

|  |  |  |  |
| --- | --- | --- | --- |
| Metric | Indicator | Unit | Formula used |
| econ1 | Production costs per capita | EUR/y | 100∙(1-norm[econ1]) |
| econ2 | Production revenue per capita | EUR/y | 100∙norm[econ2]) |
| soc1 | Social indicator – cereals | - | 100∙soc1 |
| soc2 | Social indicator – potatoes | - | 100∙soc2 |
| soc3 | Social indicator – vegetables | - | 100∙soc3 |
| soc4 | Social indicator – fruit | - | 100∙soc4 |
| soc5 | Social indicator – meat | - | 100∙soc5 |
| soc6 | Social indicator – milk and dairy products | - | 100∙soc6 |
| soc7 | Social indicator - eggs | - | 100∙soc7 |
| env1 | GHG emissions per capita | kg/y | 100∙(1-norm[env1]) |
| env2 | Mineral fertilizers use per hectare of land | t /(ha∙y) | 100∙(1-norm[env 2]) |
| env3 | Share of land for organic farming | - | 100∙env3 |
| env4 | Food and feed imported per capita | t/y | 100∙(1-norm[env4]) |
| env5 | Food and feed exported per capita | t/y | 100∙(1-norm[env5]) |
| flw1 | FLW per capita | kg/y | 100∙(1-norm[flw1]) |
| flw2 | Edible FLW per capita | kg/y | 100∙(1-norm[flw1]) |

Indicators are normalized using the method of Baratsas et al. (2022), ranging from 0 point (complete linearity) to 100 points (complete circularity). Category sub-indices are calculated as the average of category indicators, and the overall ACS index is obtained by combining category sub-indices.

* + 1. Measures for circular agriculture and sustainable food production
       1. Narrow use of fertilizers and pesticides

The Farm to Fork strategy calls for a minimum 20% reduction in fertilizer and pesticide use. Decreasing mineral fertilizer consumption can mitigate water pollution, nitrogen oxide emissions, and contribute to climate protection (European Commission, 2020). This measure also enhances agricultural circularity by enabling the utilization of waste products like compost, manure, and litter as organic fertilizer alternatives to mineral fertilizers.

* + - 1. Use regeneration strategies

The Farm to Fork strategy seeks to expand the share of land dedicated to organic food production to at least 25%. Organic farming plays a significant role in enhancing agricultural circularity by employing various measures to minimize waste and optimize resource utilization. It produces sustainable crops without resorting to artificial chemicals. Organic farms have well-established practices for recycling and composting waste, along with the utilization of organic fertilizers. Organic farmers typically raise fewer animals compared to their conventional counterparts, contributing to soil fertility preservation and pollution reduction.

* + - 1. Narrow food consumption

According to the CGR report for the Netherlands, the ratio of animal to plant protein in the human diet used to be around 40/60, while in Western countries it is now around 60/40 (Circle Economy, 2020). In Slovenia, this ratio is even higher at 68.6/31.4, leading to excessive consumption of resources for animal feed and health problems due to obesity and environmental pollution. Balancing the dietary habits with more plant-based foods and less meat consumption is an important measure for circular agriculture. For example, halving red meat consumption (RMC) would reduce total daily protein intake from 100 g per capita to 86 g and the ratio of animal to plant protein to 63.4/36.6, still providing more than enough protein for the average person, according to health recommendations.

* + - 1. Reduce waste

Minimizing food loss and waste is crucial for the circular economy, because producing food that is ultimately not eaten consumes large amounts of resources. United Nations Sustainable Development Goal 12.3 targets a 50% reduction in food loss and waste (United Nations, 2015). Edible food waste (eFLW) should be addressed through dietary changes, humanitarian initiatives, and education. Unavoidable food loss and waste should be transformed into bio-based products and bioenergy through cascading utilization.

* + - 1. Produce local

Local feed and meat production is crucial for a circular economy, according to the CGR report for the Netherlands (Circle Economy, 2020). Eliminating animal product and feed imports and exports could boost the Netherlands' circularity metric by 1.5% and reduce its material footprint by 5.4%. Prioritizing local production would lessen cross-border transportation emissions. The EU's principle of free movement of goods and services may hinder agricultural circularity and sustainability. Importing cheap food from abroad while exporting the same type of domestically produced food leads to unnecessary transportation emissions. Home-grown animals can consume local agricultural and food waste, reducing reliance on external sources. This shift would require political and financial incentives to discourage animal product imports and exports while supporting local producers through subsidies.

* + - 1. Minimize inputs, maximize outputs

Circular food production necessitates maximizing output with minimal resource utilization. According to the European Commission (2016), crop yields have increased steadily, with cereal yields rising from an average of 5 t/ha to 6.2 t/ha between 1993 and 2015, representing a 24% increase. Yield improvements are expected to continue due to technological advancements, new crop varieties, enhanced management practices, and improved organization. Considering the uncertainty surrounding these forecasts, a conservative assumption was made for the next measure: a 10% increase in yield per hectare and a 10% reduction in mineral fertilizer use over the coming decades.

* 1. Results

The estimated value of the ACS index for the current situation of Slovenian agriculture is 32.1 points (left rectangle in Figure 1), with the highest value for the Economy sub-index (45 points, grey column) following by the Environment (39, green) and Society (36, blue), while the lowest value is for the FLW sub-index (8, brown).

A screenshot of a computer screen

Description automatically generated

Figure 1: ACS index and principal category sub-indexes

Limiting mineral fertilizer use to a maximum of 80% of current levels (-20% MF in Figure 1) raises the ACS index to 54.8 points. This significant uplift stems from a substantial surge in the Society sub-index (from 36 to 95 points), primarily attributed to the enhanced local food production which is the result of the optimized distribution of agricultural land. The Environmental sub-index also experiences a substantial boost, reaching 70 points. This advancement is driven by a 66% reduction in mineral fertilizer consumption compared to the current level, coupled with an increase in the share of organic agriculture from 7.7% to 43.5%. This achievement aligns with the Farm to Fork strategy's mandate of at least 25% organic agriculture, explaining that the same optimal solution was attained also by implementing the second measure (25% OF in Figure 1).

Reducing red meat consumption by half (-50% RMC) increases the ACS index to 57.5 points. The Society sub-index value nears its maximum (99.5), indicating an abundant supply of local food. The Environment sub-index also reaches a high value of 71 points, as emissions, particularly from animal husbandry, would fall. Eliminating half of the edible FLW (-50% eFLW) would double the ACS index, surpassing the impact of all other measures. Abolishing animal product imports and exports (IMP-EXP), as proposed in the Netherlands' CGR report, would raise the ACS index. However, if meat consumption remains unchanged, this measure leads to an increase in GHG emissions and fertilizer use compared to previous measures as all animal-based foods are produced domestically. A 10% increase in agricultural productivity (10% HY, -10% MF) would additionally improve the ACS index compared to implementing the measures of Farm to Fork strategy (-20% MF and 25% OF). This improvement is primarily due to the higher Environment sub-index, as the higher productivity enables an increase in the share of organic production to 50%, which substantially reduces the use of mineral fertilizers.

Implementing all proposed measures would boost the ACS index from the current 32.1 to 67.6 points. This scenario would maximize the Society sub-index to 100 points, indicating local availability of essential food groups. This would significantly mitigate environmental impact, reduce food waste, and maintain economic performance. It is noteworthy that the ACS index of the solution obtained by maximizing the production of food and feed in our previous work (Drofenik et al., 2023) was a mere 39 points. This highlights the central role of optimization with an appropriately tailored multi-objective function. This approach can lead to solutions that not only achieve a high level of food security, but are also environmentally and economically sound.

* 1. Conclusions

A novel metric, the 'Agriculture Circularity and Sustainability index' (ACS), was introduced and integrated as a multi-criteria objective function into the MILP model to optimize the food supply chain. The ACS index enables the evaluation of agricultural sector performance and promotes circular and sustainable food production solutions. The individual impacts of six measures were assessed: reducing artificial fertilizer use, food waste production, a change of dietary habits, promoting organic farming, enhancing food production productivity, and balancing the import and export of animal-derived food. The case study for Slovenia revealed that implementing all measures would more than double the overall ACS index, from the current 32.1 points to 67.6 points. Food waste reduction and red meat consumption reduction have the most significant contributions to this improvement. Additionally, investing in increased agricultural productivity is crucial due to projected population growth and climate change.

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