ASSESSING CROP ROTATION SUSTAINABILITY USING ANALYTICAL HIERARCHY PROCESS

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KEYWORDS

Crop rotation, sustainability assessment model, multi-criteria decision analysis, AHP.

ABSTRACT

With the food security challenge faced by nations globally, agriculture sustainability has been a significant consideration for concerned agencies. Sustainability assessments are significant tools in providing support to stakeholders in their crop production planning. Agricultural sustainability assessment, however, is complex and it involves numerous criteria that can be conflicting. In this study we investigated the use Analytical Hierarchy Process, a multi-criteria decision analysis method, in assessing the sustainability of crop rotation alternatives and its applicability to address the multiple criteria of sustainability and the diverse preferences of stakeholders. The comparable results of the model with a sustainability assessment of cropping systems reported in the literature, validates AHP as an apt method for sustainability assessment of crop rotation alternatives and handling the complex criteria of sustainability and preferences of stakeholders. The model results, when well presented, can be utilized to support stakeholders in their decision making and in evaluating their crop rotation choices.

INTRODUCTION

Sustainable agriculture involves selection of crops appropriate to the location and conditions of the farm, crops diversity, proper soil management and efficient use of farm resources. It promotes crop production practices that enhances productivity and profitability (economic) without compromising the health of natural resources (environment) and the quality of life of the society (social). With the food security challenge faced by nations globally, agriculture sustainability has been a significant consideration for concerned agencies like the Food and Agriculture Organization (FAO) and United Nations (UN). Diverse innovative practices have been explored to improve sustainability. Among the crop production practices endorsed by research agencies is crop rotation, which is the planned successions of crops over time on the same field. Crop rotation has been proven to increase yield, reduce the need for synthetic inputs (i.e. fertilizer and pesticides) and enhance resilience (Stanger and Lauer 2008, Carter, et al. 2009, Lin 2011).

Numerous research methods have been exploited to advance and assess crop rotation sustainability. Crop growth simulation models have been developed to evaluate the impact of climate, water, soil, agricultural inputs and management practices on crops. Model-driven decision support system (DSS), a type of DSS that utilizes complex models, is among the approaches explored to provide support to stakeholders in agriculture in their decision making. DSS tools developed to promote crop rotation have diverse and genuine objectives, but the majority are mainly for experimental simulations, for experts use and not aimed for smallholder farmers use. Limitations on crop rotation sustainability assessment methods include: non-dynamic assessment, lack of regard to the individual crop production preferences and goals of smallholder farmers, and focused only on single years and single crops rotation.

Agricultural sustainability assessment is complex, and it involves numerous criteria that can be conflicting and stakeholders may also have different needs and priorities. One approach to address the complex criteria of sustainability is by alternatives evaluation (rather than just selecting one solution) based on indicators with the aid of multi-criteria decision methods (Dury, et al. 2012). In the critical review of Multi-Criteria Decision Analysis (MCDA) techniques in (Diaz-Balteiro, González-Pachón and Romero 2017), the results indicate that there is a proliferation on the utilization of MCDA techniques in aggregating sustainability criteria which signifies the importance of the method in this context. Furthermore, MCDA techniques have been regarded as an apt framework for assessing agricultural sustainability because of its capacity to evaluate diverse criteria and priorities (Talukder, et al. 2017).

Our research aims to investigate the integration of crop growth simulation model and multi-criteria decision analysis as an approach for a dynamic and multi-criteria sustainability assessment model which can be used to support stakeholders in their decision making. In this paper, we study the use of Analytical Hierarchy Process, an MCDA method, in assessing the sustainability of crop rotation alternatives and its applicability to address the multiple criteria of sustainability and the diverse preferences of stakeholders.

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BACKGROUND

Multi-Criteria Decision Analysis (MCDA)

The MCDA deals with the evaluation of alternatives relating to multiple and conflicting decision criteria. Alternatives are the set of options that a decision maker needs to assess, and the criteria are the factors that are being considered to attain the goal of the decision making (e.g. cost, quality). MCDA is composed of non-linear recursive process which involves structuring the decision problem, articulating and modelling the preferences, aggregation of the alternative evaluations and providing recommendations (Guitouni and Martel 1998).

MCDA methods can be classified as deterministic, stochastic or fuzzy for single or group decision making. They have been regarded as apt methods to perform sustainability assessments. In the "Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment" study by Cinelli et al. (Cinelli, Coles and Kirwan 2014), the authors reviewed the performance of MAUT (Multi attribute utility theory), ELECTRE (Elimination and choice expressing the reality), AHP (Analytical hierarchy process), PROMETHEE (Preference ranking organization method for enrichment of evaluations) and DRSA (Dominance-based rough set approach) with respect to 10 criteria under the domain of scientific soundness, feasibility, and utility. Their result indicates that most of the requirements are satisfied by the MCDA methods but with different extents. MAUT and AHP are for utility-based theory, ELECTRE and PROMETHEE are for outranking relation theory and DRSA is for the sets of decision rules theory. These methods have been the most widely employed MCDA tools in sustainability related research and the selection of which method to employ should be grounded on the basics of the approach and the type of assessment to be performed (Cinelli, Coles and Kirwan 2014).

Analytical Hierarchy Process (AHP)

The AHP method, developed by Dr. Thomas Saaty, is a theory of measurement by pairwise comparisons which derives priority scales through the experts' judgements. AHP decomposes a complex MCDA problem into a system of hierarchies, combines both qualitative input with quantitative data and supports dimensionless analysis. It has been used in different settings for decision making in various projects. The standard procedure for AHP is outlined by (Saaty 2008) as:

1. Define the problem and determine the kind of knowledge sought.
2. Structure the decision hierarchy, starting from the top to the bottom level (i.e. goal, criteria and alternatives, respectively)
3. Construct the set of pairwise comparison matrices using the fundamental scale of absolute numbers (Table 1)
4. Compute priority values and consistency ratio

The consistency ratio (CR) estimates the consistency of the pairwise comparisons and allows checking of reliability.

$$CR = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}}$$

The calculation of the consistency ratio is further explained in (Mu and Pereyra-Roxas 2017). An acceptable consistency ratio value should be less than 10%. The priority value is used to rank the alternatives. The alternative with the highest priority value can be regarded as the best by the decision maker.

Table 1: The Fundamental Scale of Absolute Numbers (Saaty 2008)

Intensity	Definition
1	Equal Importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated importance
9	Extreme importance
2, 4, 6, 8	Weak or slight, Moderate plus, Strong plus, and Very, very strong (respectively)

If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i

Sustainability Assessment and Indicators

Sustainability assessment advocates agriculture sustainability by aiding stakeholders in evaluating the sustainability impact of their crop production choices. An increasing number of sustainability assessment tools have been developed to support stakeholders, like farmers and policymakers (Olde, Bokkers and Boer 2017). Sustainability assessment approaches vary on how and what (economic, environmental, and social sustainability) indicators are measured and evaluated.

In their sustainability assessment study, Castoldi and Bechini (2010) aggregated 15 economic and environmental indicator values to come up with a global sustainability index which they used to assess the cropping systems at field level. The indicators were selected from extensive literature review based on the ability to quantify the effects of cropping systems management on the environment and on economic profitability, and data obtainability. The average and standard deviation of the indicators were calculated using a large data set of cropping systems management for 131 fields in Northern Italy, which were obtained through a 2-year periodic interviews with farmers. Figure 1 lists the 15 economic and environmental indicators which are mainly classified as economic, nutrient management, energy management, pesticide management and soil management indicators.

METHODS

With the analysis goal of evaluating the agricultural sustainability of crop rotation alternatives to support stakeholders in their decision making, the AHP method was employed and its standard procedure was followed. The following subsections give further details on these steps.

Decision Hierarchy

The sustainability indicators and alternatives identified by (Castoldi and Bechini 2010) were used in structuring the decision hierarchy. Figure 1 shows the criteria, and subcriteria to evaluate the alternatives and provide solution to the analysis goal. The crop rotation alternatives to be evaluated are continuous maize (*Mc*), maize and other crops (*Mo*), continuous rice (*Rc*), rice and other crops (*Ro*), and winter cereals (*Ce*). The permanent meadows, which was originally part of the assessment in the benchmark study, was not included due to the lack of available model parameters to simulate its impact.

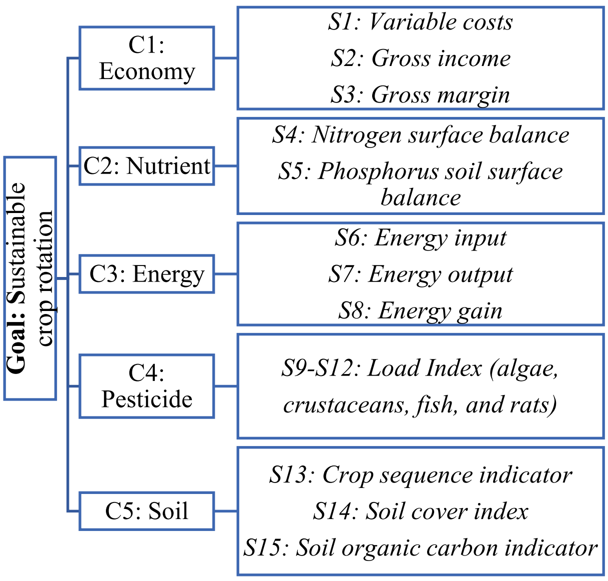

Figure 1: Goal and decision criteria based from the indicators identified by (Castoldi and Bechini 2010)

Indicator Values and Pairwise Comparison

To facilitate comparison of the goal analysis result of AHP with the sustainability assessment of (Castoldi and Bechini 2010), the same sustainability function, parameters and the average indicator values (x) from the study were used to compute the subcriteria values *(s)* of the 5 alternatives (*Mc, Mo, Rc, Ro, Ce*).

The subcriteria values of the alternatives were derived using the sustainability function:

$$f(s_i)\begin{cases}\left(\frac{x_i - S_{min}}{S_{opt1} - S_{min}}\right)^k, \textit{left side of the curve}\\ \left(\frac{x_i - S_{max}}{S_{opt2} - S_{max}}\right)^k, \textit{right side of the curve}\end{cases}$$

where x_i is the mean subcriteria value of alternative i; S_{opt1} and S_{opt2} are the lower and upper threshold values of the subcriteria, respectively; S_{min} and S_{max} are the thresholds used to define the minimum and maximum sustainable range of the indicators; k sets the linear or non-linear relationship; and, $s_i \in \mathbb{R}\,|0 \geq s_i \leq 1$. Table 2 shows the mean indicator values and the computed subcriteria values of the alternatives.

The alternatives are then compared using the derived subcriteria values (or the sustainability index) and the pairwise comparison matrices are constructed using the fundamental scale of absolute numbers. To automate the pairwise comparison process, the following pairwise function was used:

$$f(P_{ij})\begin{cases}8 * (v_i - v_j) + 1 & v_i \geq v_j\\ \frac{1}{8 * (v_j - v_i) + 1} & \textit{, otherwise}\end{cases}$$

where v_i and v_j are the corresponding subcriteria values of alternatives i and j; and, $P_{ij} \in \mathbb{R}\,|\frac{1}{9} \geq P_{ij} \leq 9$.

Table 2: Mean and Subcriteria Values of Alternatives

		Mc		Mo		Rc		Ro		Ce	
		x	*s*	*x*	*s*	*x*	*s*	*x*	*s*	*x*	*s*
C1	S1	583	0.6	445	1	692	0	466	1	188	1
	S2	1616	1	1284	0.5	2052	1	1736	1	951	0
	S3	1033	1	840	0.5	1360	1	1270	1	763	0.2
C2	S4	182	0	72	0.8	75	0.7	55	1	-18	0.3
	S5	38	0.8	0	1	-5	1	-15	1	-12	1
C3	S6	27.8	0	22	1	22.6	1	18.8	1	10.7	1
	S7	364.5	1	257.3	1	192.6	0.2	204.6	0.4	127.4	0
	S8	336.7	1	235.3	1	169.9	0.4	185.8	0.6	116.7	0
C4	S9	108.2	0.8	106.5	0.8	259.4	0	144.5	0.7	0.3	1
	S10	1.4	0.6	15.5	0	7.6	0	4.1	0	0	1
	S11	2.2	0.5	2.4	0.3	8.5	0	7.6	0	0	1
	S12	1.5	0.9	0.8	1	8.5	0	3.6	0	0.5	1
C5	S13	2	0.3	4.6	0.7	1	0.1	4.1	0.6	3.5	0.5
	S14	0.35	0.3	0.5	1.0	0.33	0	0.4	1.0	0.45	1.0
	S15	6.3	0.8	4.6	0.4	4.3	0.4	2.1	0.1	1.4	0

RESULTS AND DISCUSSION

Multicriteria Sustanability Assessment of Alternatives

Using equal weights (w) on the multiple criteria sustainability, the priority values of the alternatives were computed and is shown in Table 3. Each five criteria (C1-C5) are equally assigned a weight of 20, totaling to 100 and this weight is equally divided to the respective sub-criteria.

$$\sum_{i}^{n} C_i = 100 \textit{ and } C_i = \sum_{j}^{n} S_j$$

The results denote that the best crop alternative, with respect to the set goal criteria, is maize with other crops (*Mo*, 24%) and the least is continuous rice (*Rc,* 13.6%).

Mo outperforms the other alternatives in the energy and soil management criteria (*C3 and C5*). The priority values suggest, however, that rice and other crops (*Ro*) is more favored when it comes to the economic nutrient management criteria (*C1 and C2*) while winter cereals (*Ce*) tops the alternatives on pesticide toxicity. These results are consistent with the findings of the benchmark study. As to the reliability of the pairwise comparisons, the average consistency ratio (CR) value is 2.4% and all are within the acceptable consistency ratio value (i.e. $<$ 10%).

Table 3: Priority Values Result (Equal Criteria Weights)

	w	Mc	Mo	Rc	Ro	Ce	CR
C1	20	4.2	3	4.3	6.1	2.4	0
S1	6.67	0.6	2	0.2	2	2	2.8
S2	6.67	1.7	0.5	2.1	2.1	0.2	2.2
S3	6.67	2	0.5	2	2	0.2	2.9
C2	20	1.2	4.7	4.4	6.6	3.1	0
S4	10	0.3	2.4	2	4.6	0.7	4
S5	10	0.9	2.4	2.4	2.1	2.4	0
C3	20	5.5	6.8	2.5	3.1	2	0
S6	6.67	0.2	1.6	1.6	1.6	1.6	0
S7	6.67	2.6	2.5	0.5	0.9	0.2	4.6
S8	6.67	2.8	2.7	0.4	0.6	0.2	3.7
C4	20	4.6	3.6	0.8	1.2	9.8	0
S9	5	1.1	1.1	0.1	0.6	2.1	2.9
S10	5	1.3	0.3	0.3	0.3	3	2.7
S11	5	0.9	0.6	0.2	0.2	3	4.2
S12	5	1.3	1.7	0.2	0.2	1.7	0.4
C5	20	4.6	5.8	1.6	4.3	3.7	0
S13	6.67	0.6	2.5	0.4	1.9	1.3	1.5
S14	6.67	3.6	1.3	1	0.4	0.3	2.7
S15	6.67	0.4	2	0.2	2	2	2.5
Priority	***100***	***20.2***	***24***	***13.6***	***21.4***	***20.9***	

Addresing Diverse Preferences

To evaluate the applicability of AHP in addressing the diverse preferences of stakeholders, the crop rotation alternatives were assessed using the different criteria and sub-criteria preferences (weights) of the stakeholders (farmer, researcher, agronomist, decision maker and environmentalist) in (Castoldi and Bechini 2010). Figure 2 shows the comparison of the results of AHP with the the rankings of the said study. The rankings are labeled as numbers 1 to 5, with 1 as the best. The permanent meadows were mainly considered as most sustainable system (rank 1) in the benchmark study. However, since it was not included in the AHP ranking, the alternatives ranking in the benchmark study were subsequently adjusted (i.e. rank 2 to rank 1, rank 3 to rank 2, and so on) to facilitate comparison.

In the AHP ranking, the top 1 and 2 crop rotation alternatives among stakeholders vary between *Mo* and *Ro* while the least (5) is mainly *Rc*, with the exeption of the farmer ranking in (*b*) where the lowest rank is *Ce*. For the rank results of the benchmark study., generally, the top 1 and 2 crop rotation are also a switch between *Mo* and *Ro*, with the exeption again of the farmer ranking in (*b*) where *Mc* lands the second. *Rc* is consistently in their lowest in rank.

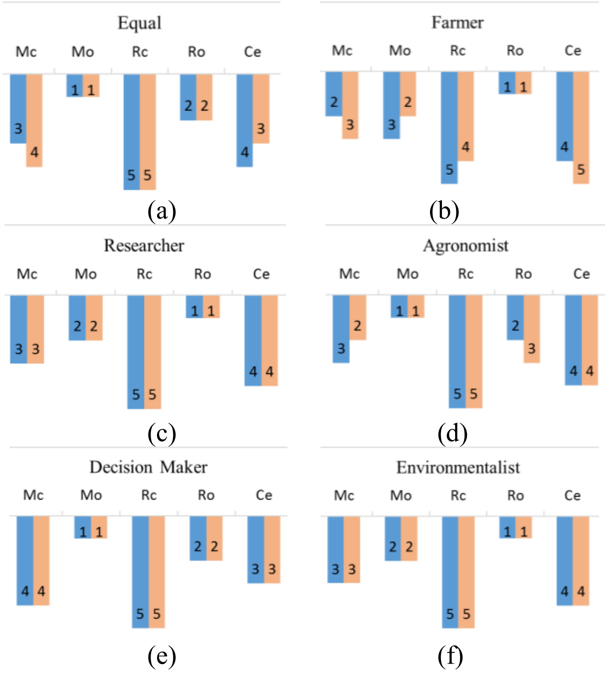

Figure 2: Comparison of Rankings per Stakeholder

Overall, the AHP ranked the same top (1) crop rotation alternative as the benchmark study's result for all stakeholder cases. This demonstrates the capability of AHP to find the best alternative. Both have corresponding rankings in *c*, *e* and *f* but with some variations in *a*, *b*, and *d*. In *a* (equal), *Mc* and *Ce* were switched as rank 2 and 3; in *b* (farmer), there is an interchange in ranks between *Mc* and *Mo*, and *Rc* and *Ce;* and in *d* (Agronomist), *Mc* and *Ro* swapped as 2nd and 3rd ranks. The priority values of the alternatives related to these swapped ranks were examined and the average priority value difference between these swaps is 0.005 (0.5%) which can be considered as negligible and hence, rationalizes the switch in ranks. The overall priority values of the stakeholder groups with switch in ranks were scaled relative to the maximum priority and were plotted as radar graphs in Figure 3. It can be noted in the chart that the alternatives switched in ranks generally falls on a contiguous radial grid or distance. These observations support the validity of the AHP method in evaluating the sustainability of crop rotation alternatives.

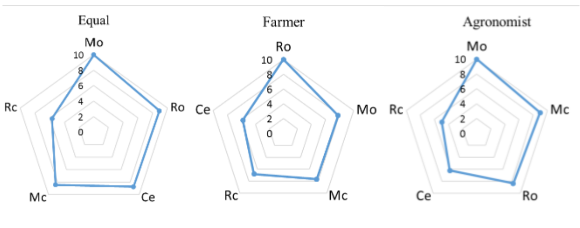

Figure 3. Scaled Priority Values of Equal, Farmer and Agronomist Rankings

CONCLUSION

In this paper, we used and investigated the applicability of Analytical Hierarchy Process as an approach to assess the agricultural sustainability of crop rotation alternatives and to address the diverse sustainability criteria and preferences of stakeholders. The output of the model was compared to the integrated sustainability assessment of the benchmark study. and the resulting ranking of the evaluated crop rotation alternatives are comparable regardless of the different inclinations of the stakeholder groups. This validates AHP as an apt method in handling the multiple and complex criteria of sustainable agriculture and the diverse preferences of stakeholders, and in assessing the sustainability of crop rotation alternatives. Moreover, the resulting priority values of AHP, when well presented, can be utilized to support stakeholders in their decision making and in evaluating their choices.

FUTURE WORK

For a dynamic agriculture and multi-criteria sustainability assessment, we plan to investigate the integration of a crop growth simulation model and the MCDA method.

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