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A Multi-Criteria and Dynamic Sustainability Assessment of Crop Rotation Alternatives

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A MULTI-CRITERIA AND DYNAMIC SUSTAINABILITY ASSESSMENT

OF CROP ROTATION ALTERNATIVES

by

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ABSTRACT

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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. Limitations on crop rotation sustainability assessment methods include: non-dynamic assessment; lack of regard to cover crops and to the individual crop production preferences of farmers; and focused only on single-year and single-crop rotation. We sought to address these limitations by developing a multi-criteria and dynamic sustainability assessment model that considers the economic and environmental impact of a multi-year and multi-crop rotation. In this study, we investigated the integration of a crop simulation model, multi-criteria decision analysis and an ontology-based cover crop model as an approach. The integration allows dynamic assessment of multi-crop and multi-year crop rotation by having the crop model simulate the potential crop production of alternatives based on the provided model parameters, weather, and agromanagement data. The crop rotation and cover crop effects and benefits are also accounted for by using the asserted and inferred knowledge of the cover crop ontology. Finally, a multi-criteria assessment of the crop rotation alternatives is possible by the integration of analytical hierarchy process, a multi-criteria decision analysis method.

To my husband, Mike, and daughter, Mikaela,
My parents, Saturnino† and Justina,
My siblings, Nestor, Roger, Noel, Nerlyn and Junna,
And to all my supportive relatives, friends and mentors,
whose unwavering love, kindness, guidance, encouragement and prayers,
have helped me overcome all the challenges,
and succeed in this Ph.D. journey.
I dedicate this dissertation to you.
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CHAPTER 1

INTRODUCTION

Food security and sustainable agriculture are two of the challenges faced by nations globally. As a population grows, the demand for food rises. To keep up with the demand without compromising the environment, sustainable agriculture techniques are significantly being studied and advocated by concerned local, national, and international organizations. The United Nations (UN) furthers sustainable agriculture through its Sustainable Development Goal 2 (SDG 2) which endeavors to "*end hunger, achieve food security and improved nutrition, and promote sustainable agriculture*". Smallholder farming households, which has an estimated global population of 500 million (around 2 billion people), rely on small-scale agriculture for their livelihoods and they play a key role in the attainment of this goal. Facilitating multi-criteria and dynamic sustainability assessment of crop rotation alternatives can support them accordingly in their crop production planning and abet the advocacy of agriculture sustainability[1].

Sustainable agriculture has been a significant consideration for concerned agencies like the US Department of Agriculture (USDA), Food and Agriculture Organization (FAO), and the Sustainable Agriculture Research and Education (SARE) program. Numerous research methods have been exploited to advance and assess agricultural sustainability. Some sustainability assessment studies consider only one or more aspect (environmental, economic, and social) of sustainability [1]. For decision support efforts, the design is either expert-driven (e.g. agriculture experts, policy makers), stakeholder-driven (e.g. farm owners, farmers, ranchers), or both.

[1] IEEE Transactions and Journals style is used in this thesis for formatting figures, tables, and references.

In 2015, through its SDG 2, the UN has set specific goals to achieve by 2030. Among these goals, are to double the agricultural productivity and income of small-scale food producers (*SDG 2, target 2.3*), and to ensure sustainable food production systems and implement resilient agricultural practices (*SDG 2, target 2.4*) [2]. To support the attainment of these SDG 2 targets, this research is focused on upholding sustainability in the crop production practices of small-scale food producers.

1.1 Theoretical Formulations

Sustainable agriculture integrates three main objectives – environmental health, economic profitability, and social and economic equity [3]. 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). This involves selection of crops appropriate to the location and conditions of the farm, crops diversity, proper soil management, and efficient use of farm resources. Diverse innovative practices have been explored to improve sustainability. Among the crop production practices endorsed by government and research agencies on sustainable agriculture are crop rotation and cover crops [4, 5, 6].

1.1.1 Crop Rotation and Cover Crops

Crop rotations are planned sequences of crops on the same field to improve soil nutrient levels, break pest cycles, and reduce production risk [7]. By rotating crops with different nutrient needs and alternating deep and shallow rooting plants, good soil health and structure are achieved [8]. Crop rotation has also been proven to increase yield, reduce the need for synthetic inputs (i.e. fertilizer and pesticides), and enhance resilience [9, 10, 11].

Cover crops, on the other hand, are crops grown primarily to maintain soil fertility and productivity and not solely for harvesting. It is sometimes referred to as *green manures* and *catch crops* – a crop that catches the nutrients after the main crop. Cover crops offer several benefits including erosion control, insect and weed suppression, soil conservation and soil health, and with careful selection, they can fit into any crop rotation or cropping system [12].

1.1.2 Smallholder Farmers

Smallholder farmers are small-scale agricultural producers who cultivate land plots smaller than 2 hectares of owned or rented land [13, 14]. Eighty-four percent (84%) of all farms are smaller than 2 hectares [15]. Smallholder family farming are small farms that depends primarily on family labor. It is considered as the backbone of agricultural production in developing countries as 80% of these countries' food is a product of small-scale farms [16].

1.1.3 Decision Support Tools on Sustainable Crops Production

Numerous research methods and tools have been developed to promote sustainable crops production. Model-driven DSS, a type of decision support system (DSS) that utilizes complex models, is among the approaches explored to provide support to stakeholders in agriculture in their decision making. Crop growth simulation models have been developed to evaluate the impact of climate, water, soil, agricultural inputs and management practices on crops. Crop models, like WOFOST (WOrld FOod Studies), simulates crop growth based on eco-physiological processes and how these processes are influenced by environmental conditions [17]. Furthermore, DSSAT (Decision Support System for Agrotechnology Transfer) is an example of a decision support system which integrates over 42 crop simulation models to simulate growth, development, yield, and multi-year outcomes of crop management strategies [18].

Crop rotation models, on the other hand, have been an integral part of crop production DSS in assessing the impact of different crop rotation practices. Optimization using linear programming is the most widely used modeling technique in identifying the best crop combination with respect to a specific objective. Optimization objectives vary depending on the priorities and needs of the intended end-users. It could be to maximize the farmer's expected profit [19], or to optimize the use of land by selecting the best mix of crops to cultivate [20], or to select crops based on trade-offs between economic and environmental factors. Moreover, some studies combine tools to find the optimal crop combination. In [21], the researchers integrated a crop growth model and linear programming and in [22], software components were integrated using their associated input and output streams.

Agricultural sustainability assessment is complex, 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 [23]. In the critical review of Multi-Criteria Decision Analysis (MCDA) techniques in [24], 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 [1]. The Analytical Hierarchy Process (AHP) is one of the well-known and widely used MCDA methods [25, 26].

Research efforts and DSS on cover crops have also been developed to help farmers in their cover crops selection. DSS tools like the Cover Crop Decision Tools by Midwest Cover Crops Council [27] and Cover Crops for Vegetable Growers by Cornell University [28] consolidates information and rates cover crops based from the gathered information (through literature, research results, on-farm experience, and practical knowledge). Cover crops information are found on websites, databases or hard-coded in programs in different structures which makes it hard to find, reuse, and analyze. Web ontologies have been known for allowing the sharing of a common understanding of the structure of information and enabling reuse of domain knowledge [29]. An ontology of cover crops would, therefore, facilitate extraction and aggregation of information from different sources of data.

1.2 Purpose

This research endeavors to advocate sustainable agriculture and contribute to the realization of SDG 2 by developing a sustainability assessment model that could simulate the economic and environmental impact of crop production practices. Specifically, this study seeks to aid in the attainment of SDG 2 targets 2.3 (increase agricultural productivity and income of small-scale food producers) and 2.4 (ensure sustainable food production system and practices) by concentrating mainly on the sustainability assessment of crop rotation and cover crops production practices of smallholder farmers.

1.3 Problem Statement

With the challenges on agriculture sustainability, numerous research methods and tools have been built to promote sustainable crops production. Government and research agencies involved with sustainable agriculture endorse crop rotation and cover crops as sustainable practices and tools that have been developed to promote these practices and aid stakeholders.

Crop rotation models have diverse and genuine objectives, but the majority are mainly for experimental simulations, for experts use and not aimed for smallholder farmers. Limitations on crop rotation sustainability assessment methods include: non-dynamic assessment; lack of regard to the individual crop production preferences of smallholder farmers; and focused only on single-year and single-crop rotation. On the other hand, cover crops data are stored in various formats, databases and applications which makes it difficult to aggregate data and limits data sharing. This study thus aims to address these limitations and answer the following research questions:

1) Can AHP assess the sustainability of crop rotation alternatives and address the multiple criteria of sustainability and the diverse preferences of stakeholders?
2) Can the sustainability impact of a multi-year and multi-crop rotation be assessed dynamically by incorporating a crop growth model with AHP?
3) Can cover crops concepts and guides be formally represented in an ontology to provide guidance to smallholder farmers on their cover crops selection?
4) Can these modeling techniques be integrated to facilitate multi-criteria and dynamic sustainability assessment of crop rotation alternatives?

1.4 Proposed Method and Procedure

This research aims to develop a multi-criteria and dynamic sustainability assessment model that considers the economic and environmental impact of a multi-year and multi-crop rotation. The model will integrate a crop simulation model, multi-criteria decision analysis, and an ontology-based cover crop model as an approach for a multi-criteria and dynamic sustainability assessment of crop rotation alternatives as shown in Fig. 1.

The crop rotation assessment model will be developed by employing a crop model and AHP method to allow assessment of the diverse sustainability criteria and to account for the preferences and priorities of smallholder farmers. An ontology of the cover crop concepts and selection guides will be created to formally represent the concepts and rules on cover crop selection. Lastly, these modeling techniques will be integrated into a multi-criteria and dynamic sustainability assessment model for crop rotation alternatives.

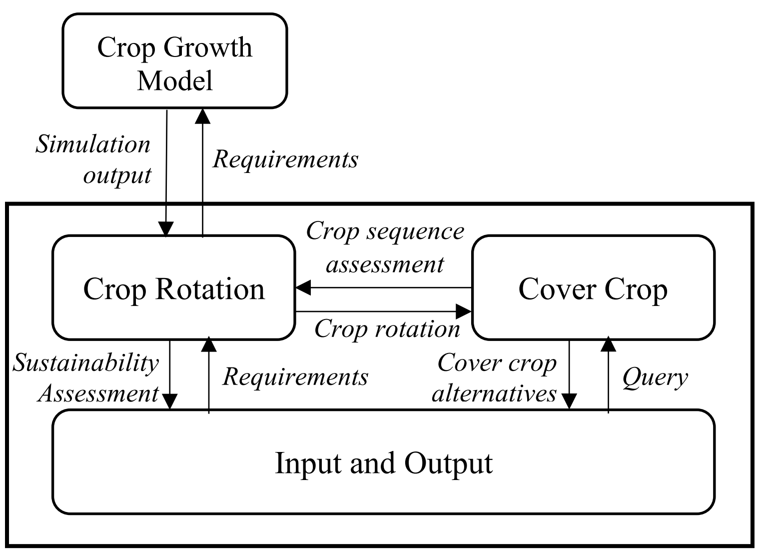


Fig. 1. Schematic diagram of the components of the sustainability assessment model. The main components of the model are the: 1) crop rotation; 2) crop growth model; and 3) cover crops. The arrows denote the flow of information from one component to another.

1.5 Contributions

This study hopes to contribute to the attainment of UN's SDG 2 goal of promoting agriculture sustainability by developing a sustainability assessment model for crop rotation alternatives. The use of crop rotation and cover crops have shown positive effects on crop yield and soil health [30, 31]. With informed decisions, smallholder farmers could take advantage of the various benefits that each cover crop and crop rotation can provide based on their individual management goals. The model will facilitate multi-criteria and dynamic sustainability assessment of crop rotation alternatives which can aid smallholder farmers accordingly in their crop production planning and abet the advocacy of agriculture sustainability by increasing awareness of the sustainability impact of their choices. Specifically, this research is expected to contribute the following:

1) A crop rotation sustainability assessment model that:
    a) integrates a crop growth model and AHP for a dynamic and multi-criteria evaluation of crop rotation alternatives;
    b) assess impact of a multi-year and multi-crop rotation using economic and environmental indicators; and,
    c) integrates a cover crop ontology to account for the effect of cover crops;
2) A semantic data model of cover crops using ontology to facilitate extraction, aggregation and inferring of cover crop knowledge; and,
3) An ontology-based crop sequence assessment model.

1.6 Organization of Dissertation

The succeeding chapters are organized into seven parts. Chapter 2 (Background) presents the background concepts and relevant research on the sustainable crops production practices particularly on crop rotation and cover crops. The research questions are addressed in the next chapters in the following order: 1) Chapter 3 tackles the first research question; 2) Chapters 4 and 5 takes on the second; 3) Chapter 6 for the third; and, 4) Chapter 7 for the last research question.

In Chapter 3 (Sustainability Assessment Using AHP), we investigate the use of an MCDA method – the Analytical Hierarchy Process (AHP), in assessing the sustainability of crop rotation alternatives and its applicability to address the multiple criteria of sustainability and the diverse preferences of stakeholders. Next, the use of WOFOST as a tool to simulate the multi-year and multi-crop rotation of alternatives is presented in Chapter 4 (Multi-Year and Multi-Crop Rotation Using Wofost). In the same chapter, we examine the utilization of the simulation results for a dynamic sustainability assessment of alternatives.

We then discuss the integration of a crop simulation model and AHP as an approach for a dynamic and multi-criteria sustainability assessment of crop rotation alternatives in Chapter 5 (Integration of AHP and PCSE for A Multi-Criteria and Dynamic Sustainability Assessment). In Chapter 6 (A Semantic Data Model of Cover Crops), a semantic data model of cover crops using ontology is designed and built to facilitate extraction, aggregation, and inferring of cover crop knowledge. Subsequently, in Chapter 7 (An Ontology-Based Crop Sequence Assessment), we utilize the cover crop ontology and integrate it to the crop rotation assessment model to assess the crop sequence indicator of a crop rotation.

Finally, the dissertation is concluded and recommendation for further studies are presented in Chapter 8 (Conclusion and Future Work).

CHAPTER 2

BACKGROUND

To be able to develop a decision support tool that upholds sustainability in the crops production practices of smallholder farmers, it is imperative to understand the underlying sustainable crops production concepts and practices (i.e. crop rotation and cover crop) and existing implementations. The following subsections will discuss the background concepts and relevant researches on these topics.

2.1 Sustainable Crops Production

Sustainable agriculture 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). According to Feenstra et al. [3] from the University of California - Sustainable Agriculture Research and Education Program (UC SAREP), sustainable crop production practices involve various approaches which considers the topography, soil characteristics, climate, pests, local availability of inputs, and the individual grower's objectives. Fig. 2 presents the general principles that can be applied in the selection of appropriate management practices. These principles are reinforced by the USDA-SARE program [6] which lists crop diversity and cover crops among the practices that contributes to long-term farm profitability, environmental stewardship and improved quality of life. This study will be adhering to these principles by employing a crop model that considers soil, crop history, and location information; developing crop rotation and cover crops model to promote diversification of crops, soil management and efficient use of inputs; and having a design that regards the individual goal of smallholder farmers.

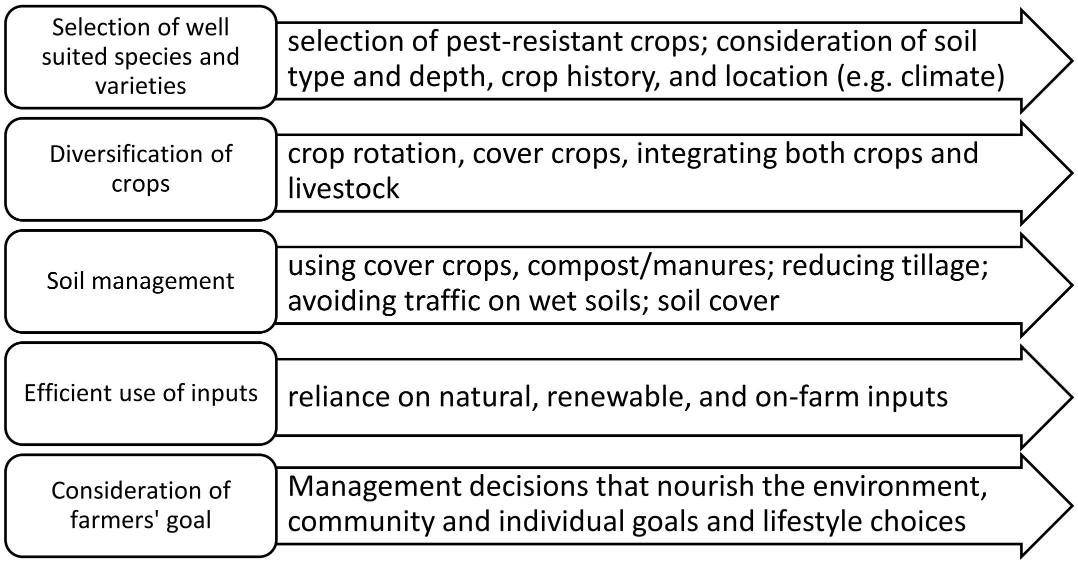


Fig. 2. General crop production principles by Feenstra et al. [5].

2.2 DSS on Crops Production

DSS are applications that are utilized by different stakeholders primarily to provide assistance in their decision making. The main components of a DSS are the database, model, and user interface. The crop rotation DSS studies in the literature employ diverse modeling techniques to represent the crop rotation process and find the best crop succession. Dury et al. [23] reviewed the models that support crop planning and crop rotation decisions in more than 120 references and investigated how these concepts were formalized and used. The review summary in Table 1 denotes that the studies vary on their approach on identifying the succession of crops, on their set of objectives, and how they resolved the problem. Each of these approaches offer solutions to crop rotation issues that could aid farmers in their decision making.

TABLE 1

CROP ROTATION MODELING TECHNIQUES AS REVIEWED BY DURY ET AL. [23]

	Technique	Description
Crop succession representation	Predefined by expert	Fixed set of crop succession
	Rules and agronomic filter	Flexible crop sequences based on user-controlled rules and filter (e.g. inclusion/exclusion/sequence rules)
	Indicators	Flexible crop sequences based on indicators (e.g. effect of preceding crop, diversity)
	Probability of crop occurrence	Flexible crop sequences based on observed or historical data on crop rotations
	Reducing factors	Flexible crop sequences based on factors reducing crop yields (e.g. predefined reducing factor, yield estimate of preceding crop by regression analysis)
Objectives	Socio-economic	The objective accounts for profit, equipment and/or labor
	Agronomy environment	The objective accounts for irrigation, energy, nutrient, pesticide, herbicide and/or soil
Problem resolution	Optimization	Finds best crop rotation using linear, non-linear or evolutionary programming
	Expert system	Use rules that are based on expert knowledge in finding the best crop rotation
	Evaluation	Evaluation of alternatives based on indicators, rather than selecting only the best crop rotation

2.3 Cover Crops

Cover crops can be generally considered as any non-cash crop grown in addition to the primary cash crop [32]. There are several types of plants that can be used as cover crops, but the most common types are legumes (e.g. soybeans, peanuts, peas, beans) and grasses (e.g. sudan grass, ryegrass, corn, wheat). These crops offer several benefits (e.g. increase soil organic matter, protect the soil from erosion, improve soil structure and water infiltration, increase soil fertility, and break pest and disease cycles). One of the biggest challenges of cover cropping is fitting them into a crop rotation to take full advantage of their benefits [33]. The benefits of cover crops are fully maximized when the unique characteristics, tradeoffs, and management concerns of these crops are taken into consideration. Thus, the success and profitability of cover crop adoption depends upon suitable selection of crops based on the management goals of the farmer. Among the points to consider on cover crops selection are the current and next cash crop, the available time windows, site-specific information, and specific goals.

2.4 Related Studies

The following sections present a list of studies that are related and employed in this research.

2.4.1 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 [34]. Indicator-based 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 [35] 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, 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 2-year periodic interviews with farmers. Fig. 3 lists the 15 economic and environmental indicators which are mainly classified as economic, nutrient management, energy management, pesticide management, and soil management indicators. Labor or equipment were not included as indicators due to difficulty in

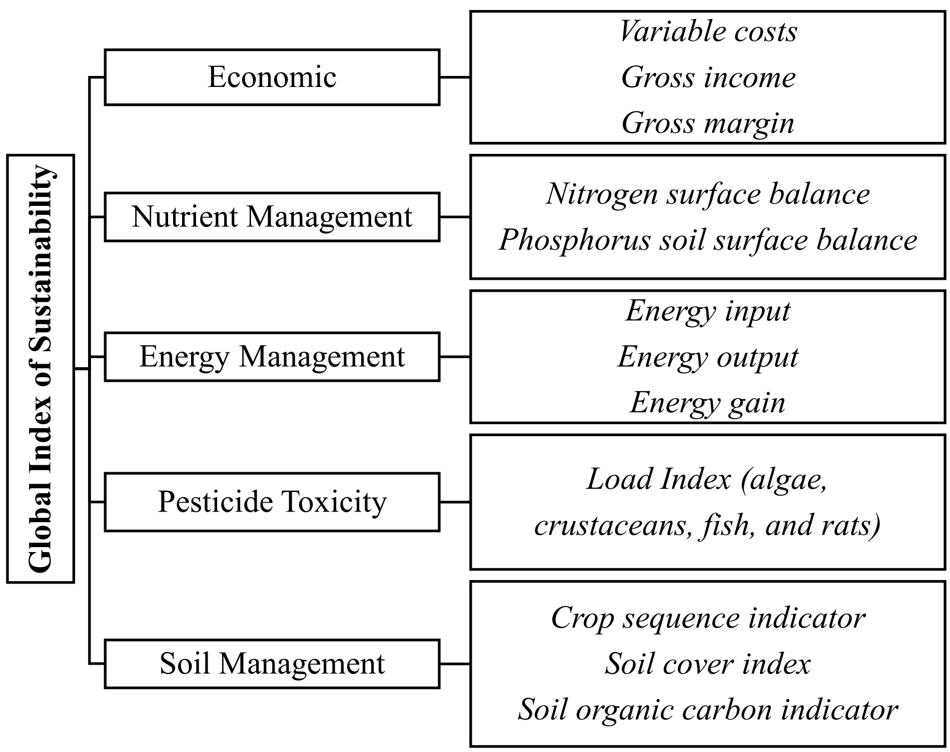


Fig. 3. Economic and agro-ecological indicators used for the evaluation of cropping systems sustainability by [35].

the quantification of human labor or machine time among different crops (e.g. time or associated cost needed or spent in each field operation, depreciation allowance, rent of machinery).

Furthermore, the cropping systems they evaluated are continuous maize or corn (*Mc*), maize and other crops (*Mo*), continuous rice (*Rc*), rice and other crops (*Ro*), winter cereals (*Ce*), and permanent meadows (*Pm*).

2.4.2 Multi-Criteria Decision Analysis

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 processes which involves structuring the decision problem, articulating and modelling the preferences, aggregation of the alternative evaluations, and providing recommendations [36].

MCDA methods 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. [37], 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 [37].

2.4.3 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP), developed by Dr. Thomas Saaty, is an MCDA method, which decomposes a complex MCDA problem into a system of hierarchies. It is a theory of measurement by pairwise comparisons which derives priority scales through the experts' judgements [38]. 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 in [38] 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.
4) Compute priority values and consistency ratio.

The consistency ratio (also referred to as inconsistency ratio) 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 [39]. 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.

According to Saaty, AHP has been used in different settings for decision making in various projects (e.g. public administration, disaster & risk management, dispute/conflict resolution, promotion, admission) by notable organizations like IBM, Ford, British Airways, Xerox Corporation, and the US Nuclear Regulatory Commission.

Structuring the hierarchy

AHP allows structuring of complex MCDA problems into hierarchies which facilitates the evaluation of the alternatives based on the identified criteria and sub-criteria. A collection of over 400 government and private sector decision problems that are structured as hierarchical decision models are presented in the *"Hierarchon: A dictionary of hierarchies"* [40]. Fig. 4 illustrates an example of AHP hierarchy. The first level is the goal (G), followed by the control or group criteria (C1, C2) and the covering sub-criteria (S1, S2, S3, S4). The last level (represents the alternatives that are to be evaluated with respect to the set criteria.

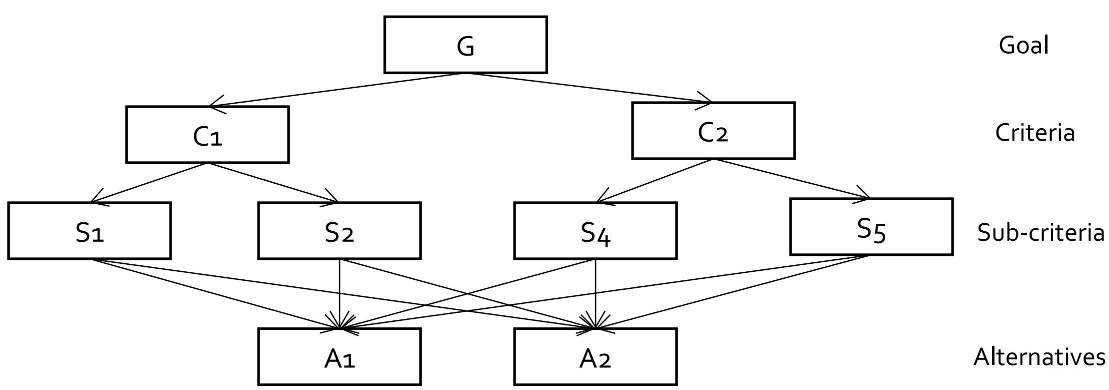


Fig. 4. Example AHP hierarchy.

Constructing the set of pairwise comparison matrices

In constructing the pairwise comparison matrices, Satty recommends the fundamental scale of absolute numbers in TABLE 2. Using the scale, comparisons are made between alternatives for each criterion and the results are recorded in a reciprocal matrix:

$$\mathrm{A}_i = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & a_{ij} & \\ \dots & 1/a_{ij} & 1 & \\ a_{n1} & & & 1 \end{bmatrix}$$

where a_{ij} is the pairwise comparison of alternatives i and j and $a_{ji} = 1/a_{ij}$. The matrix below shows an example in which the fundamental scale is used to compare the three alternatives with respect to criteria S1:

$$\mathrm{A}_{S1} = \begin{array}{cccc} & A1 & A2 & A3 \\ A1 & 1 & 2 & 1/2 \\ A2 & 1/2 & 1 & 1/5 \\ A3 & 2 & 5 & 1 \end{array}$$

The matrix denotes that with regard to criteria S1, A1 is slightly more important than A2 and is slightly less important than A3. On the other hand, A3 is slightly more important compared to A1 and strongly more important than A2. For every criterion, a pairwise comparison matrix is constructed.

Deriving priorities

There are several methods proposed for deriving priorities. In [41], the authors discuss 18 estimating methods for deriving preference values which includes the eigenvalue and geometric mean methods. The geometric mean has been supported by a group of AHP community due to the absence of rank reversals using the method. Saaty's group, however, advocates the eigenvalue method [42]. The eigenvalue approximation can be recapped into three steps:

1) calculate the sum of the columns, sum_j, of the pairwise matrix ($sum_j = \sum_{i=1}^{n} a_{ij}$),

2) normalize the columns by dividing each a_{ij} with the corresponding sum of column ($a'_{ij} = a_{ij}/sum_j$),

3) derive the average of each row, to derive the priority vector ($p = \sum_{j=1}^{n} a'_{ij}$)

TABLE 2

THE FUNDAMENTAL SCALE OF ABSOLUTE NUMBERS BY SAATY [38]

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	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*	

Rank reversal

In [43], the authors pointed out the rank reversal problem with the eigenvalue method. Satty has provided several counterexamples that show rank reversals should be allowed. He rationalizes the rank reversal in [44], stating that rank reversal occurs due to the fact that "*the priorities of the alternatives are weighted by the priorities of the criteria that depend on the measurements of the alternatives*", hence, "*the overall ranking of any alternative depends on the* *measurement and number of all the alternatives"*. To avoid rank reversal, Satty suggests the use of the ideal mode of AHP instead of the distributive mode. That is, to compare each performance score to a fixed benchmark (e.g. to the best alternative under a specific criterion). The distributive synthesis mode, however, is apt when the decision maker is concerned with the performance of each alternative compared to all other alternatives under a criterion.

Different priority derivation methods have been proposed to avoid the rank reversal problem and the geometric mean method is among them. Comparison and simulation results show that there is no distinct difference between the two methods [41]. The authors of [45] observed a high level of agreement between the different scaling techniques and that the dimension of the matrix and the inconsistencies influences the number of ranking contradictions. These contradictions, however, impact close priorities only.

2.4.4 World Food Studies (WOFOST)

WOFOST is a mechanistic simulation model that supports quantitative analysis of the growth and production of annual crops growing at any location based on the underlying processes (e.g. photosynthesis, respiration, and environmental conditions). It is maintained and further developed by Wageningen Environmental Research (Alterra) in collaboration with the Plant Production Systems Group of Wageningen University & Research and the Agri4Cast unit of the Joint Research Centre in Italy. WOFOST has been tested by various researchers worldwide and has been applied for many crops of different climatic and management conditions [17].

The model requires crop, soil, and weather input data sets and allows selection of the production level (potential, water limited, and nutrient limited crop growth), crop calendar (start and number of years of simulation, options for start and end of crop), soil fertility parameters (basic soil supply of nitrogen (N), phosphorus (P) and potassium (K) and the output options. The crop growth is simulated with time steps of one day based on eco-physiological processes. Its main processes are phenological development, CO2-assimilation, transpiration, respiration, light interception, partitioning of assimilates to the various organs, and dry matter formation. The model provides daily time step results and summary of results for both potential, and water-limited crop production.

The summary of results includes simulated data on total dry weight of storage organs, total above ground production, water balances of the whole system and the root zone, and, the amount of fertilizer that are needed to acquire potential or water-limited production. These output data are very significant and can be utilized to assess the sustainability impact of a specific crop or crop rotation.

2.4.5 Ontology

An ontology defines the terms [and their relationships] used to describe and represent an area of knowledge and makes this knowledge reusable [46]. The Web Ontology Language (OWL) from the World Wide Web Consortium (W3C) is a semantic web modeling language for expressing ontologies and are exchanged as Resource Description Framework (RDF) documents. Ontology editors like Protégé, a free and open-source editor developed by the Stanford Center for Biomedical Informatics Research, facilitate creation of ontologies and supports the W3C OWL 2 standards. Fig. 5 illustrates that ontology can be thought of either as an abstract structure or as an RDF graph. The top part are the various syntax formats and at the bottom are the two semantic specifications.

The ontology structure mainly consists of classes, properties, and relationships. Classes provides a description of concepts in the domain of interest, properties are features, and attributes of the concepts, and relationships denotes the interconnections of these concepts. Another important feature of OWL 2 is that it captures the human intelligence of drawing consequences from their knowledge [47]. Reasoners, like HermiT and Pellet, are tools that infer logical consequences from a set of asserted facts. Noy et al. [29] outlines some of the possible reasons for developing an ontology as:

- sharing of common understanding of the structure of information among agents and people (i.e. search across or aggregate information from different sources of data);
- enabling reuse of domain knowledge (i.e. reuse and integrate existing ontologies);
- making domain assumptions explicit;
- separating domain knowledge from the operational knowledge (i.e. knowledge is independent from the program or algorithm); and,
- analyzing domain knowledge (i.e. the declarative knowledge facilitates formal analysis of terms).

For the abovementioned reasons and its recognizable benefits, ontologies have been used in diverse areas and industries (e.g. healthcare, biomedical, agriculture, manufacturing, and communications) to abet management of significant mass of data. For agriculture data, the cropontology.org and planteome.org are examples of organizations that compile ontologies of the anatomy, structure, and phenotype of crops.

SPARQL (SPARQL Protocol and RDF Query Language Ontologies) is utilized to express queries across diverse data sources including RDF. It supports RDF graph manipulation including aggregation, subqueries, negation, creating values by expressions, extensible value testing, and constraining queries [48]. The data in ontologies, which are stored in RDF format, can be accessed using SPARQL.

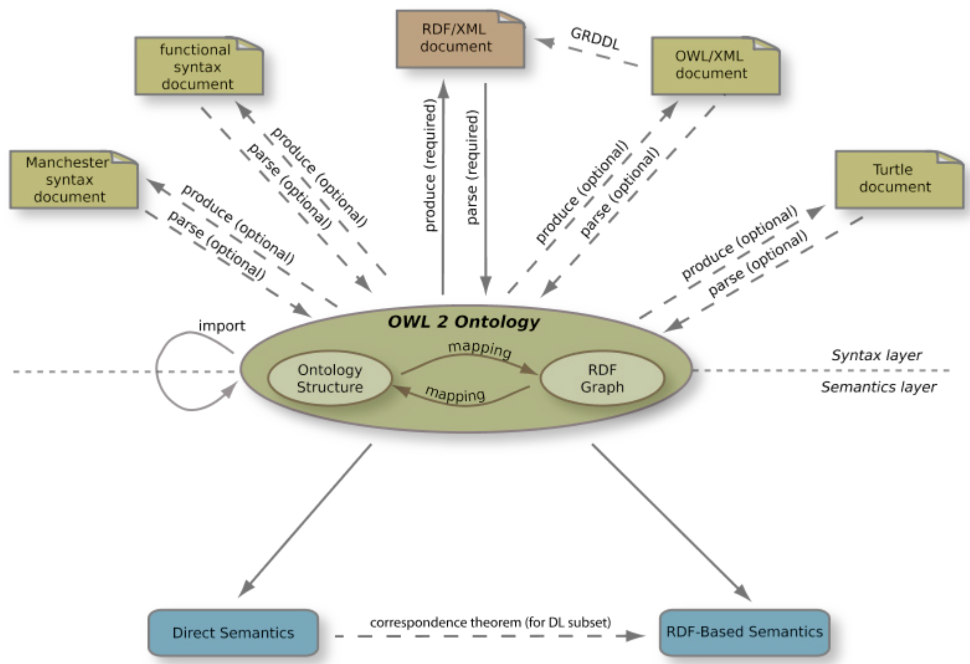


Fig. 5. Structure of OWL 2 by W3C [49]. Copyright © 2012 W3C® (MIT, ERCIM, Keio), All Rights Reserved. W3C liability, trademark and document use rules apply.

CHAPTER 3

SUSTAINABILITY ASSESSMENT USING ANALYTICAL HIERARCHY PROCESS

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 chapter, 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.

3.1 Decision Hierarchy, Sub-criteria Values, and Pairwise Comparison

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 using the AHP package developed by Christoph Glur. The package was implemented in R and it can be accessed at https://github.com/gluc/ahp. The following subsections give further details on the decision hierarchy, the indicator values, and pairwise comparison used in the AHP model.

3.1.1 Decision Hierarchy

The sustainability indicators and alternatives identified by Castoldi and Bechini [35] (referred to as *benchmark study*) were used in structuring the decision hierarchy. Fig. 6 shows the criteria, and sub-criteria employed 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.

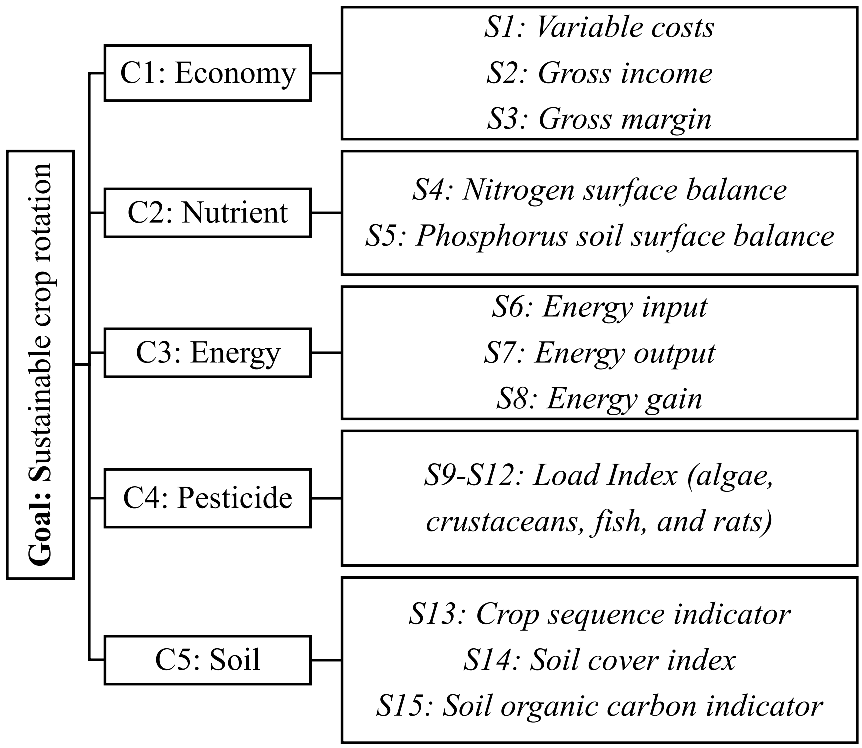


Fig. 6. Goal and decision criteria based from the indicators identified in the benchmark study.

3.1.2 Sub-criteria Values and Pairwise Comparison

To facilitate comparison of the goal analysis result of AHP with the sustainability assessment of the benchmark study, the same sustainability function, parameters, threshold, and the average indicator values ($\bar{x}$) from the study were used to compute the sub-criteria values *(s)* of the 5 alternatives (*Mc, Mo, Rc, Ro, Ce*). These data are presented in Appendix A.

The equivalent sub-criteria values of the alternatives for each indicator were derived using the sustainability function adapted from the benchmark study:

$$f(s_{ij}) = \begin{cases} \left(\dfrac{x_{ij} - S_{min_i}}{S_{opt1_i} - S_{min_i}}\right)^{k_i}, \textit{left side of the curve} \\ \\ \left(\dfrac{x_{ij} - S_{max_i}}{S_{opt2_i} - S_{max_i}}\right)^{k_i}, \textit{right side of the curve} \end{cases} \quad (1)$$

where x_{ij} is the average value of alternative j for indicator i; S_{opt1_i} and S_{opt2_i} are the lower and upper threshold values of indicator i, respectively; S_{min_i} and S_{max_i} are the thresholds used to define the minimum and maximum sustainable range of the indicator; k_i sets the indicator's linear or non-linear relationship; and, $\{s \in \mathbb{R} \mid 0 \leq s \leq 1\}$. Table 3 shows the mean indicator values ($\bar{x}$) and the computed sub-criteria values (s) of the alternatives.

TABLE 3

MEAN INDICATOR VALUES AND COMPUTED SUB-CRITERIA VALUES

Criteria		Mc		Mo		Rc		Ro		Ce	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
C1	S1	583	0.58	445	1.00	692	0.00	466	1.00	188	1.00
	S2	1616	1.00	1284	0.54	2052	1.00	1736	1.00	951	0.00
	S3	1033	0.95	840	0.54	1360	1.00	1270	1.00	763	0.21
C2	S4	182	0.00	72	0.75	75	0.71	55	0.95	-18	0.32
	S5	38	0.79	0	1.00	-5	1.00	-15	0.98	-12	1.00
C3	S6	27.8	0.00	22	1.00	22.6	1.00	18.8	1.00	10.7	1.00
	S7	364.5	1.00	257.3	0.99	192.6	0.22	204.6	0.37	127.4	0.00
	S8	336.7	1.00	235.3	0.99	169.9	0.44	185.8	0.62	116.7	0.00
C4	S9	108.2	0.83	106.5	0.83	259.4	0.00	144.5	0.65	0.3	1.00
	S10	1.4	0.60	15.5	0.00	7.6	0.00	4.1	0.00	0	1.00
	S11	2.2	0.47	2.4	0.33	8.5	0.00	7.6	0.00	0	1.00
	S12	1.5	0.94	0.8	1.00	8.5	0.00	3.6	0.00	0.5	1.00
C5	S13	2	0.29	4.6	0.66	1	0.14	4.1	0.59	3.5	0.50
	S14	0.35	0.33	0.5	1.00	0.33	0.00	0.4	1.00	0.45	1.00
	S15	6.3	0.81	4.6	0.43	4.3	0.38	2.1	0.09	1.4	0.04

The alternatives are then compared using the derived sub-criteria values and the pairwise comparison matrices are constructed relating to the fundamental scale of absolute numbers. To automate the pairwise comparison process, the following pairwise function was used:

$$f(\mathrm{a}_{jk}) = \begin{cases} 1 + 8 * |\mathrm{s}_{ij} - \mathrm{s}_{ik}| & \mathrm{s}_{ij} \geq \mathrm{s}_{ik} \\ \dfrac{1}{1 + 8 * |\mathrm{s}_{ij} - \mathrm{s}_{ik}|} & , otherwise \end{cases} \qquad (2)$$

where s_{ij} and s_{ik} are the corresponding sub-criteria values of alternatives *j* and *k,* respectively; and $\{\mathrm{a} \in \mathbb{R} \mid \frac{1}{9} \leq \mathrm{a} \leq 9\}$, which represents the resulting pairwise comparison value of alternatives *j* and *k* with respect to sub-criteria *i*. Equation 2 is derived from $X \sim U(a, b)$ where $a = 1, b = 9$, representing the highest and lowest value in the fundamental scale of absolute numbers. Using the uniform random variate, X is thus computed as:

$$X = \mathrm{a} + (\mathrm{b} - \mathrm{a})U$$

To compare the values of the two alternatives, the absolute difference of $\mathrm{s}_{ij} - \mathrm{s}_{ik}$ is computed and is assigned as U. By substitution, X is then derived as:

$$X = 1 + 8 * |\mathrm{s}_{ij} - \mathrm{s}_{ik}|$$

Lastly, the priority values of the alternatives and the consistency ratio are computed. The alternative with the highest priority value can be regarded as the best crop rotation alternative.

Obtaining the sub-criteria values

To compute for the sub-criteria values of the alternatives*,* we first identify the parameter values to calculate the sustainability functions for each indicator. For this evaluation, we are using the sustainability function parameter values presented in Appendix A.2 and the mean indicator values are shown in Table 3 (also in Appendix A.3). For *S1* indicator, the sustainability function parameters are S_{opt2} = 532, S_{max} = 653 and k = 1. Using Equation 1, the *S1* sub-criteria values of the alternatives are then calculated as:

$$s_{1j} = \left(\frac{\mathrm{x}_{1j} - 653}{532 - 653}\right)^{1}$$

For *Mc*, which has a mean indicator value x = 583, its sub-criteria value for *S1* is therefore computed as:

$$s_{11} = \left(\frac{583 - 653}{532 - 653}\right)^{1} = 0.58$$

The sub-criteria value of an alternative is set to 1 when its indicator value is within the optimum range ($S_{opt\ values}$) and is set to 0 when below S_{min} and above S_{max} [35]. For example, both *Mo*, *Ro,* and *Ce*'s indicator values ($\mathrm{x}_{12} = 445, \mathrm{x}_{14} = 466, \mathrm{x}_{15} = 188$) are within the optimum range (i.e. S_{opt2} = 532 and below, since the objective for indicator *S1* is to minimize), hence, their sub-criteria values are set to 1. On the other hand, *Rc* which has an indicator value ($\mathrm{x}_{13} = 692$) is over the indicated S_{max} parameter value, thus, its sub-criteria value is set to 0. Similar steps are done for sub-criteria *S2* to *S15* and the computed sub-criteria values (*s*) of the alternatives are shown in Table 3.

Obtaining the priority values

To obtain the overall priority values of the alternatives, the pairwise comparison matrices for each sub-criterion are constructed using a pairwise function equation (Equation 2). For sub-criteria *S1*, we construct its pairwise matrix by comparing each alternative's corresponding S1 sub-criteria value (*Mc* = 0.58, *Mo* = 1.00, *Rc* = 0.00, *Ro* = 1.00 and *Ce* = 1.00) using the pairwise function equation. Comparing *Mc=0.58* and *Mo=1*, we get:

$$\mathrm{a}_{12} = \frac{1}{1 + 8 * |\mathrm{s}_{ij} - \mathrm{s}_{ik}|} = \frac{1}{1 + 8 * |0.58 - 1|} = 0.23$$

and for *Mc=0.58* and *Rc=0* comparison, we derive,

$$\mathrm{a}_{13} = 1 + 8 * |\mathrm{s}_{ij} - \mathrm{s}_{ik}| = 1 + 8 * |0.58 - 0| = 5.64$$

We do the same steps for all upper diagonal and derive the lower triangular matrix by using the reciprocal values of the upper matrix. Table 4 shows the derived pairwise comparison matrix for sub-criteria, *S1*. Note that the sub-criteria values of *Mo* and *Ro* are equal, thus, have equal importance while the *Ro* has extreme importance over *Rc* due to extreme difference of 1. Consistent with the fundamental scale of rating, $a_{24} = 1$ while $a_{43} = 9$.

TABLE 4

PAIRWISE COMPARISON MATRIX FOR SUB-CRITERIA, S1

	Mc	Mo	Rc	Ro	Ce
Mc	1.00	**0.23**	**5.64**	**0.23**	**0.23**
Mo	4.36	1.00	**9.00**	**1.00**	**1.00**
Rc	0.18	0.11	1.00	**0.11**	**0.11**
Ro	4.36	1.00	9.00	1.00	**1.00**
Ce	4.36	1.00	9.00	1.00	1.00

The next steps are to normalize the matrix and derive the mean of rows by:

1) getting the sum of the columns, sum_k, of the pairwise matrix ($sum_k = \sum_{j=1}^{n} a_{jk}$);
2) normalizing the columns by dividing each a_{jk} with the corresponding sum of column ($a'_{jk} = a_{jk}/sum_k$);
3) deriving the average of each row, to derive the local priority ($lp_{ij} = \sum_{k=1}^{n} a'_{jk}$) of alternative *j* in sub-criteria *i;* and

4) multiplying the priority weights to obtain the priority value $(p_{ij} = lp_j * w_i)$ of alternative j in sub-criteria i.

The results of these steps are presented in Table 5. To obtain the overall priority values, the same steps are performed for each sub-criteria and the resulting weighted priority values of each alternative are aggregated.

TABLE 5

NORMALIZED TABLE AND DERIVED PRIORITY VALUES FOR S1

Sum of Columns (sum_k)					
	Mc	Mo	Rc	Ro	Ce
S1	14.26	3.34	33.64	3.34	3.34

↓

Normalized Matrix (a'_{jk})					
S1	Mc	Mo	Rc	Ro	Ce
Mc	0.07	0.07	0.17	0.07	0.07
Mo	0.31	0.30	0.27	0.30	0.30
Rc	0.01	0.03	0.03	0.03	0.03
Ro	0.31	0.30	0.27	0.30	0.30
Ce	0.31	0.30	0.27	0.30	0.30

↓

S1	Local Priority Value (lp_j)	Weighted Local Priority Value (p_{ij}) $w_i = 6.67$
Mc	0.09	0.60
Mo	0.29	1.93
Rc	0.03	0.20
Ro	0.29	1.93
Ce	0.29	1.93

3.2 Multi-Criteria Sustainability Assessment and Addressing Diverse Preferences

The following sections present the results of the multi-criteria sustainability assessment of crop rotation alternatives using AHP.

3.2.1 Multi-Criteria Sustainability Assessment of Alternatives

Using equal weights (*w*) on the multiple criteria of sustainability, the priority values of the alternatives were computed and are shown in Table 6.

TABLE 6

PRIORITY VALUES RESULT (EQUAL CRITERIA WEIGHTS)

Criteria	w	Priority Values (%)					CR
	%	*Mc*	*Mo*	*Rc*	*Ro*	*Ce*	%
C1	20	4.3	2.9	4.3	6	2.3	
S1	6.67	0.6	1.9	0.2	1.9	1.9	2.8
S2	6.67	2	0.5	2	2	0.2	2.9
S3	6.67	1.7	0.5	2.1	2.1	0.2	2.2
C2	20	1.2	4.8	4.4	6.7	3.1	
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	5.6	6.8	2.5	3.1	2	
S6	6.67	0.2	1.6	1.6	1.6	1.6	0
S7	6.67	2.8	2.7	0.4	0.6	0.2	3.7
S8	6.67	2.6	2.5	0.5	0.9	0.2	4.6
C4	20	4.6	3.7	0.8	1.3	9.8	
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	3.6	
S13	6.67	0.6	2.5	0.4	1.9	1.3	1.5
S14	6.67	0.4	2	0.2	2	2	2.5
S15	6.67	3.6	1.3	1	0.4	0.3	2.7
Priority	100	20.3	24	13.6	21.4	20.8	

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.

$$w_i = \frac{w_c}{n}$$

where w_c = weight of criteria C; w_i= weight of sub-criteria i; and n = number of $C's$ sub-criteria.

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%). Fig. 7 indicates that *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 *(C4)*. These results are consistent to the findings of the benchmark study. As to the reliability of the pairwise comparisons, the average inconsistency ratio (CR) value is 2.4% and all are within the acceptable CR value (i.e. < 10%). The derived priority values enable analysis of the sustainability impact of the crop rotation alternatives which, when presented aptly, can support smallholder farmers in their decision making.

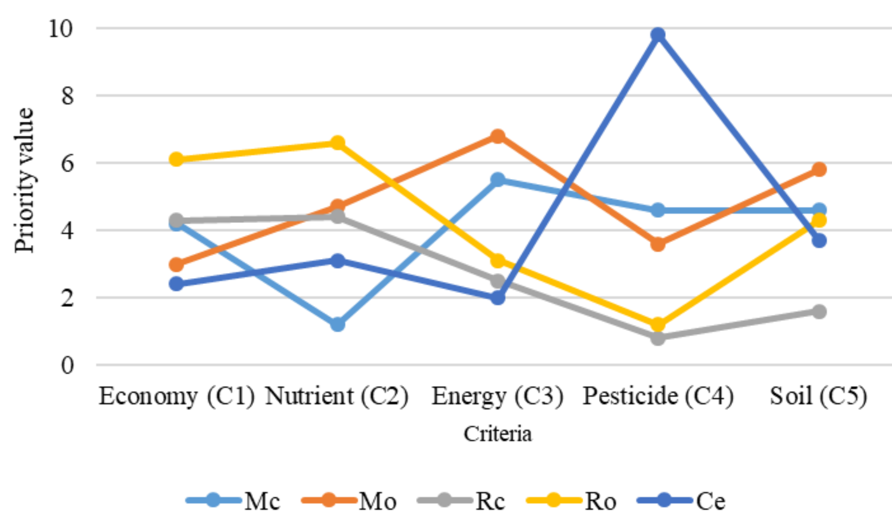
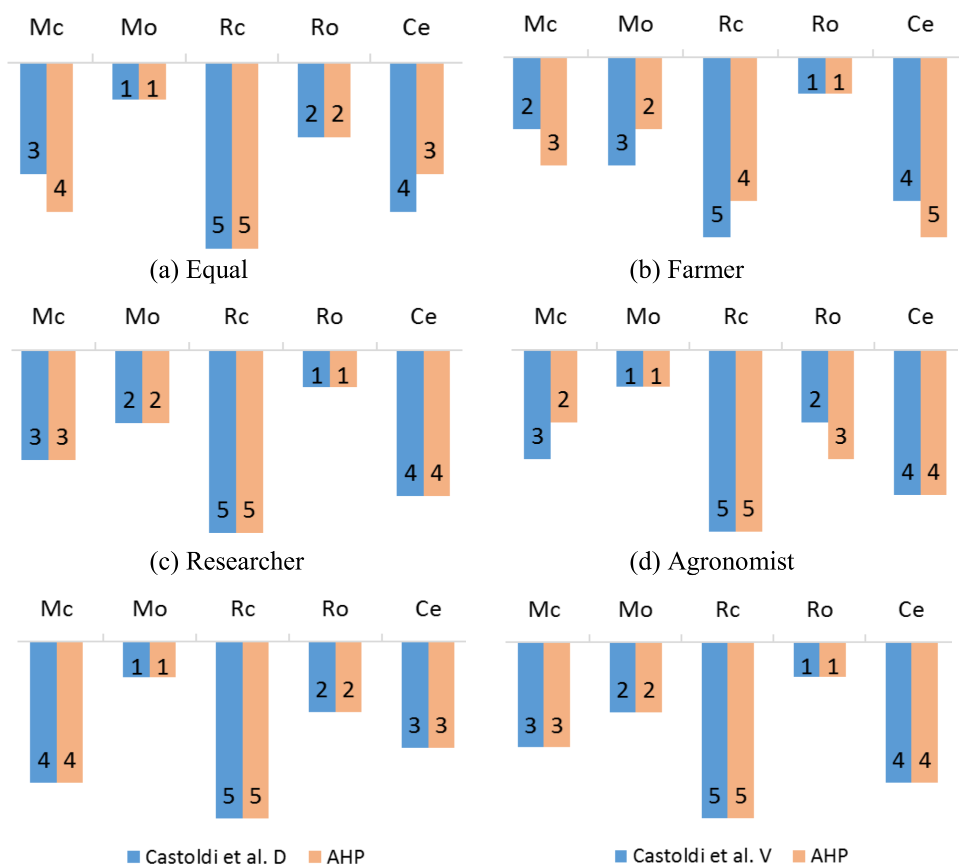


Fig. 7. Priority values of alternatives per criterion.

3.2.2 Addressing 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 the benchmark study. The detailed AHP results per stakeholder are presented in Appendix B and the benchmark study's rankings are shown in Appendix A. Fig. 8 shows the comparison of the results of AHP with the rankings of the said study.



(a) Equal (b) Farmer
(c) Researcher (d) Agronomist
(e) Decision Maker (f) Environmentalist

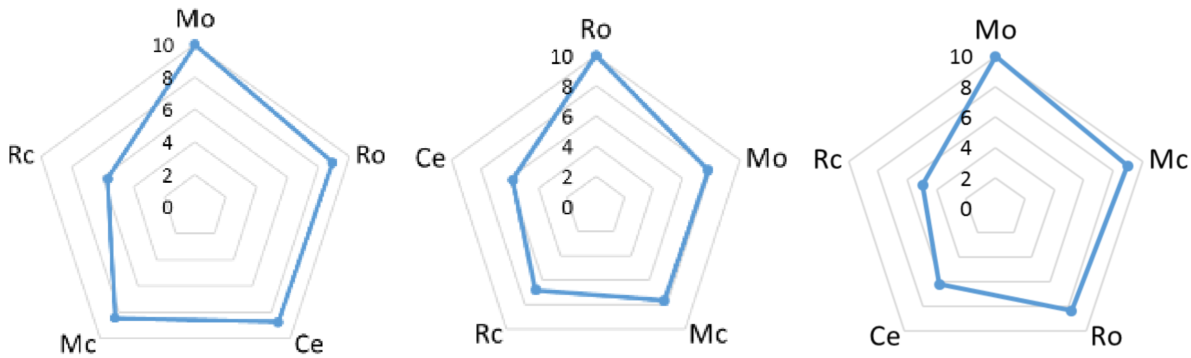
Fig. 8. Comparison of rankings per stakeholder.

The rankings are labeled as numbers 1 to 5, with 1 as the best. The permanent meadows were mainly considered as the 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, except for 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 exception again of the farmer ranking in (b) where Mc lands the second. Rc is consistently the lowest in rank.

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, hence, rationalizes the switch in ranks. The overall priority values of the stakeholder groups with a switch in ranks were scaled relative to the maximum priority and were plotted as radar graphs in Fig. 9.

It can be noted in the chart that the alternatives switched in ranks generally fall on a contiguous radial grid or distance. These observations support the validity of the pairwise function used in comparing the crop rotation alternatives. Furthermore, it strengthens the validity of the

AHP method in evaluating the multiple criteria of sustainability and the diverse preferences of stakeholders.



(a) Equal (b) Farmer (c) Agronomist

Fig. 9. Scaled priority values of stakeholder groups with a switch in ranks.

CHAPTER 4

MULTI-YEAR AND MULTI-CROP ROTATION USING WOFOST

One of the limitations of crop rotation sustainability assessment methods is that they are focused only on single-year and single-crop rotation. In this chapter, we investigate the use of WOFOST, a crop simulation model, as a tool to simulate the multi-year and multi-crop rotation of alternatives. Subsequently, we examine the utilization of the simulation results for a dynamic sustainability assessment of alternatives.

4.1 Crop Simulation using WCC and PCSE

To provide a dynamic and multi-criteria sustainability assessment of crop rotation alternatives, we sought to examine the integration of a crop model and the AHP method. First, we assessed the applicability of the AHP method in addressing the multiple criteria of sustainability and the diverse preferences of smallholder farmers as presented in Chapter 3. Next, we investigate the utilization of WOFOST crop simulation model using the WOFOST Control Center (WCC) and the Python Crop Simulation Environment (PCSE) to simulate the crop growth of alternatives and to address the limitation on single year and single crop rotation. Finally, we obtain and validate the needed simulation output variables for the sustainability assessment.

4.1.1 Crop Simulation using WCC-WOFOST

To investigate the utilization of WOFOST in simulating the crop growth of alternatives, we used the WOFOST Control Center (WCC) to simulate the yield of the *Mc*, *Rc,* and *Ce* alternatives (*Mo* and *Ro* were not included in the experiment due to the limitation of the application to handle multiple cropping). We focused on one of the economic indicators, the gross income, which is the product of the alternative's yield and its price. The daily weather data input for the model was acquired from the NASA Langley Research Center (LaRC) POWER Project [50] funded through the NASA Earth Science/Applied Science Program. The coordinates of the South Milan Agricultural Park in Italy (45°N, 9°E) were used. Unit and format conversions were implemented to the POWER weather data to conform to the required weather data format (CABO Format) of the simulation model. The NASA POWER and WOFOST weather data formats are shown in Table 7. Vapor pressure (e) was derived using the dew point temperature (Td) as mentioned in [51].

$$e = 0.611(10^{S_d}), and\ S_d = \frac{7.5T_d}{237.3 + T_d}$$

TABLE 7

WEATHER DATA UNIT OF MEASUREMENT

Variable	NASA POWER	WOFOST
Irradiation	MJ m-2 day-1	kJ m-2 day-1
Minimum temperature	degrees Celsius	degrees Celsius
Maximum temperature	degrees Celsius	degrees Celsius
Early morning vapor pressure (e)	T_d in degrees Celsius	kPa
Mean wind speed	m s-1	m s-1
Precipitation	mm day-1	mm day-1

Table 8 lists the set of input data supplied into the crop model. The *start year* was set to 2002 and a consecutive 5-year simulation was performed. The *crop files* were primarily selected based on the regions and the simulated season of the crop model. The *variable sowing dates* (earliest and ultimate) used were based from the crop sowing dates window indicated in the benchmark study. The *soil type* was set to EC2-medium being that the primary type of soil of the study area are loam, sandy-loam, and silt-loam. Moreover, the *end day* was set to end at the respective maturity stage of the alternatives.

TABLE 8

INPUT DATA FOR THE WCC MODEL

Parameter	Settings		
Start year	2002		
Consecutive years	5		
Weather	South Milan (45˚N, 9˚E)		
Crop	Maize: Grain maize 203 Rice: Rice_IR72 Winter Cereals: Winter wheat 105		
Start day	Variable sowing date	Earliest	Ultimate
	Maize: End of March to April	85	120
	Rice: Mid-April to end of May	100	150
	Winter Cereals: October or November	275	335
End day	Maturity (<= max duration)		
Soil	EC2-medium		

The gross income was calculated using the simulated average total dry weight of storage organs (TWSO) multiplied by the average 5-year farmgate price of the crop. The historical data of price was acquired from the FAOSTAT database [52] of UN's Food and Agriculture Organization (FAO). Fig. 10 displays the annual producer price of maize, rice, and wheat for Italy. These are the prices received by the farmers at the point of initial sale or at the farmgate.

4.1.2 Crop Simulation Using PCSE-WOFOST

To address the limitation of the WCC in handling multiple cropping system, we examined the use of PCSE, a Python package that implements the WOFOST crop simulation model. The PCSE 5.3 provides the *YAMLCropDataProvider* and the *AgroManager* which enables specification of parameter sets for crop rotations. To establish the simulation using PCSE, the following steps were carried out:

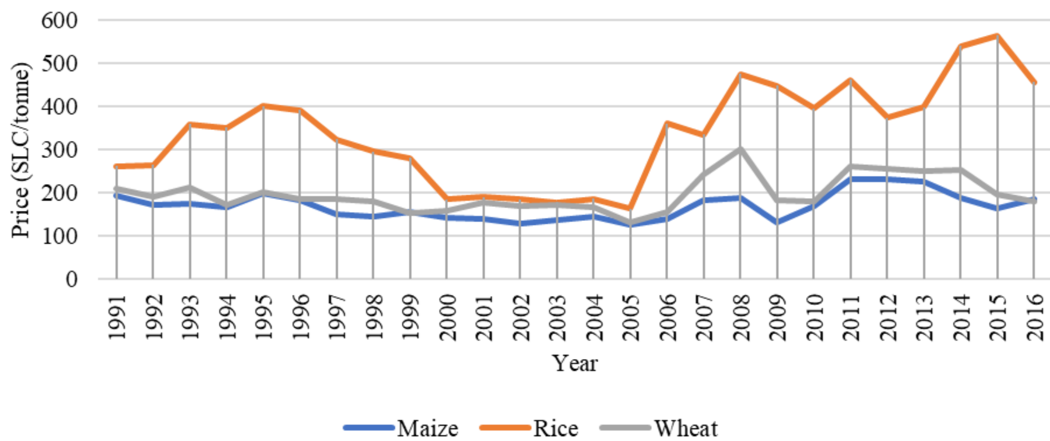


Fig. 10. Annual producer price of crops from FAOSTAT database.

i. Set up and install PCSE Environment

A python environment for PCSE was set up through the Anaconda version 5.2 with Python 3.6. The PCSE version 5.3 was installed in the environment using the *pip* package installer. The Anaconda is the most popular Python data Science platform and is a fast and convenient way to do Python and R data science and machine learning [53]. It can be downloaded from https://www.anaconda.com/download/. The PCSE, on the other hand, can be accessed from https://github.com/ajwdewit, a github repository managed by the Dr. Allard de Wit, a researcher from Wageningen Environmental Research. An installation guide and overview of the PCSE engine, models, modules, and simulation objects can also be found in [54].

ii. Set input data

The PCSE/WOFOST requires three main inputs, the a) model parameters; b) weather data; and c) agromanagement. The model parameters include the parameters of the crops being simulated, the specific site, and soil parameters of the location. The weather data holds the daily weather variables. Whereas, the agromanagement contains the specific farm activities.

iii. Simulate multi-year and multi-crop rotation

PCSE's agromanager allows the stipulation of crop calendars, rotations, timed events, and state events. The agromanagement specifies the start date of the agricultural campaign, the start date and type, the end date and type, and the maximum duration of the crop simulation. To facilitate comparison with the benchmark study, the values assigned to these dates were grounded on the cropping dates windows indicated in [55]. Using the *Wofost71_PP* model and the obtained input data, the potential yields of the crop rotations were simulated for multiple years starting from 2004 to 2006 – the same span covered and aggregated by the benchmark study.

iv. Obtain and validate gross income, energy output and soil cover index from simulation results

After running the simulation, the next task is to utilize the simulation results for the sustainability assessment. Among the indicators in the benchmark study, the gross income (GI), energy output (EnOUT) and soil cover index (SCI) are the indicators that could be acquired from the crop simulation results of the *Wofost71_PP* model. The gross income is the product of the crop's yield and its price. The energy output is defined in the benchmark study as the energy content of the crop's above ground biomass and the soil cover index is the soil cover percentage. Once the needed simulation output variables to derive the gross income, energy output and soil cover index indicators were identified, the outcomes were validated by comparing the resulting indicator values with the indicators of the benchmark study.

4.2 Simulating Crop Growth Using WCC-WOFOST and PCSE-WOFOST

The following sections present the results of the multi-year and multi-crop rotation of alternatives using WCC-WOFOST and PCSE-WOFOST, and the utilization of the simulation results for a dynamic sustainability assessment of alternatives.

4.2.1 Simulating Crop Growth Using WCC-WOFOST

The simulated yield, average crop farmgate price and the computed income are presented in Table 9. Fig. 11 shows the comparison of the simulated and the benchmark study's average gross income.

TABLE 9

SIMULATED YIELD AND INCOME

Crop	Yield (kg h-1) *Simulated*		Crop price (€ kg-1)	Income (€ h-1) *Simulated*		Income (€ h-1) *Benchmark*	
	$\bar{x}$	*SD*	$\bar{x}$	$\bar{x}$	*SD*	$\bar{x}$	*SD*
Maize (Mc)	13956	857	0.13428	1874.01	115.08	1616.00	194.00
Rice (Rc)	12701	2864	0.21372	2714.46	612.09	2052.00	389.00
Winter wheat (Ce)	6466	1466	0.15812	1022.40	231.80	951.00	574.00

The simulated and computed gross income of the alternatives were fed into the AHP model and the sustainability impact and ranking of alternatives showed similar results when the data from the benchmark study were used. We also simulated the yield for the succeeding five years (2007-2011) and the results in Fig. 12 demonstrates a significant decrease in yield in 2011 for *Mc* (12%)

and *Rc* (22%) compared to their corresponding yield estimate in 2006. *Ce*, on the other hand, retains its average yield in general except for a slight dip (3%) in 2008.

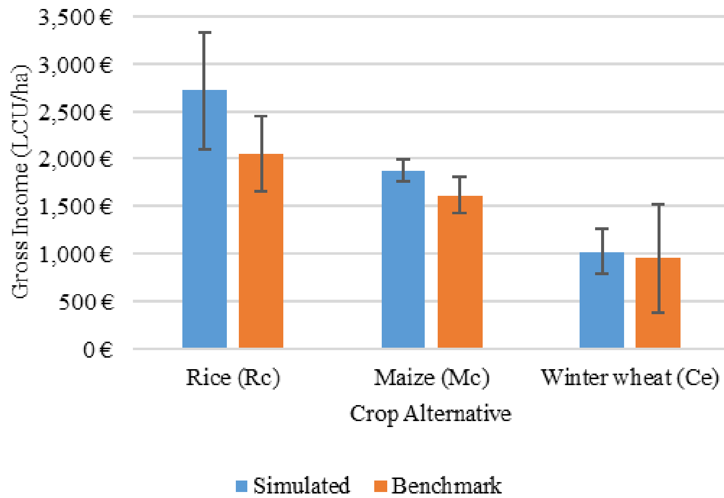


Fig. 11. Average gross income comparison.

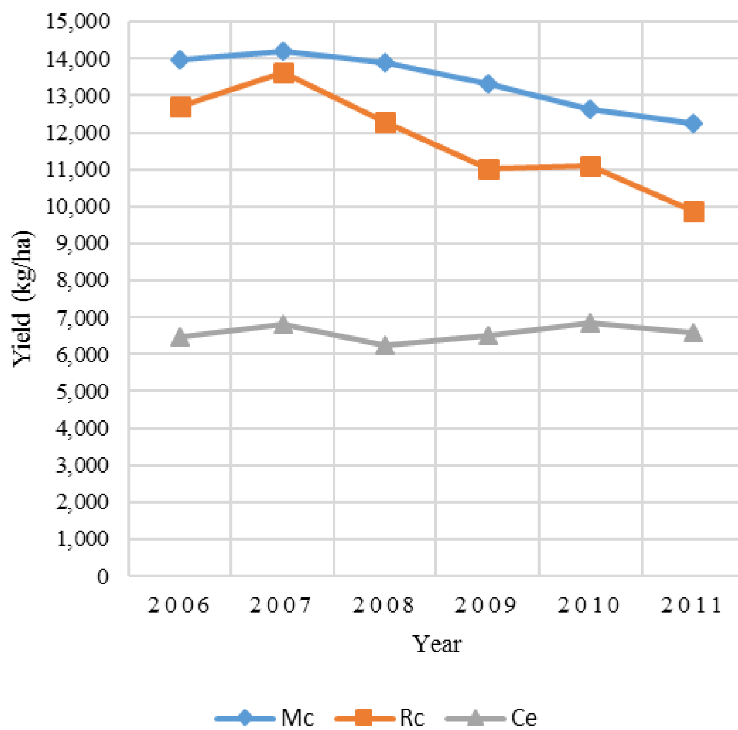


Fig. 12. Simulated average yield of alternatives.

These changes in yield impose an impact to the crop prices and the overall sustainability assessment of alternatives which are valuable to the decision making of smallholder farmers. However, with a non-dynamic assessment method, these changes are not apparent which could lead to wrong decisions. This demonstrates the significance of integrating a crop simulation model into the sustainability assessment tool for a dynamic assessment of the indicators. Moreover, the crop simulation model offers a more efficient way of evaluating the impact of alternatives compared to monitoring cropping systems in the field.

4.2.2 Simulating Crop Growth Using PCSE-WOFOST

In the previous section, we have validated the gross income data obtained by using the simulated yield of WOFOST via the WCC and have demonstrated the significance of integrating a crop simulation model into the sustainability assessment tool. The WCC, however, has limitations on handling multiple cropping system which the PCSE tackles using its *YAMLCropDataProvider* and *AgroManager* modules. Additionally, since PCSE is built in Python, integration and interfacing would be more straightforward compared to the WCC, which was developed in Fortran. In this section, we investigate obtaining data from the WOFOST implementation of PCSE.

Input data

For this simulation, the crop parameters were retrieved directly from PCSE's github repository using the *YAMLCropDataprovider*, the crop parameter data provider of PCSE. The soil parameters for EC2-medium, on the other hand, were acquired from the WCC. For the weather data input, the agroclimatology daily weather data specific to the coordinates of the South Milan

Agricultural Park (45°N, 9°E) was acquired from the NASA POWER [50] and converted to an Excel format readable by the *ExcelWeatherDataProvider* of PCSE. The required parameters and unit of measurement of the PCSE weather data are similar to that of WCC as presented in Table 7. Furthermore, an agromanagement template was set up for a multi-year and multi-crop rotation. Fig. 13 displays a sample agromanagement template written in YAML (YAML Ain't Markup Language) format, a human friendly data serialization standard for all programming languages [56].

```
agro_crop = """
- {start_date}:
    CropCalendar:
        crop_name: {crop_name}
        variety_name: {variety_name}
        crop_start_date: {start_date}
        crop_start_type: {crop[start_type]}
        crop_end_date: {year}-{crop[end_date]}
        crop_end_type: harvest
        max_duration: {max_duration}
    TimedEvents: null
    StateEvents: null
"""
```

Fig. 13. Agromanagement template.

The crop calendar indicates the crop schedule for sowing or emergence and harvesting. Whereas, the timed and state events specify management actions (e.g. fertilizer application, irrigation) at a particular date or development stage. For this, simulation, both the timed and state events were set to null since there is no detailed information about the farmers' management actions in the benchmark study. The template is then formatted using the *format()* string method, loaded using the YAML parser and assigned to the agromanagement parameter. Below is a sample assignment expression:

agromanagement = yaml.load(agro.format(start_date = start, crop_name = crop, year = year,

variety_name = variety, max_duration = max, crop=agro_dates[crop]))

where *start*, *crop*, *variety*, *year, max,* and *agro_dates* are the respective parameter values. The variable a*gro_dates* is a Python dictionary which stores the crop schedule of the crop rotation alternatives.

Multi-year and multi-crop rotation simulation

The agromanagement is an essential input in setting up the crop rotation simulation. The agromanagement parameter values employed in the model are listed in Table 10. The M, W, R represents single crop rotation while MW and RW are multi-crop rotation (i.e rotation of Maize and Winter wheat, and Rice and Winter wheat, respectively).

TABLE 10

AGROMANAGEMENT DATA FOR THE PCSE MODEL

Parameter	M	W	R	MW	RW
Crop name	Maize	Wheat	Rice	M: Maize W: Wheat	R: Rice W: Wheat
Variety name	Grain Maize 203	Winter Wheat 105	Rice 501	M: Grain Maize 203 W: Winter Wheat 105	R: Rice 501 W: Winter Wheat 105
Start month	Mar	Nov	Apr	M: May W: Oct	R: May W: Oct
Start type	sowing				
End date	Sep 30	Jul 31	Sep 30	M: Sep 30 W: Apr 30	R: Sep 30 W: Apr 30
End type	harvest				

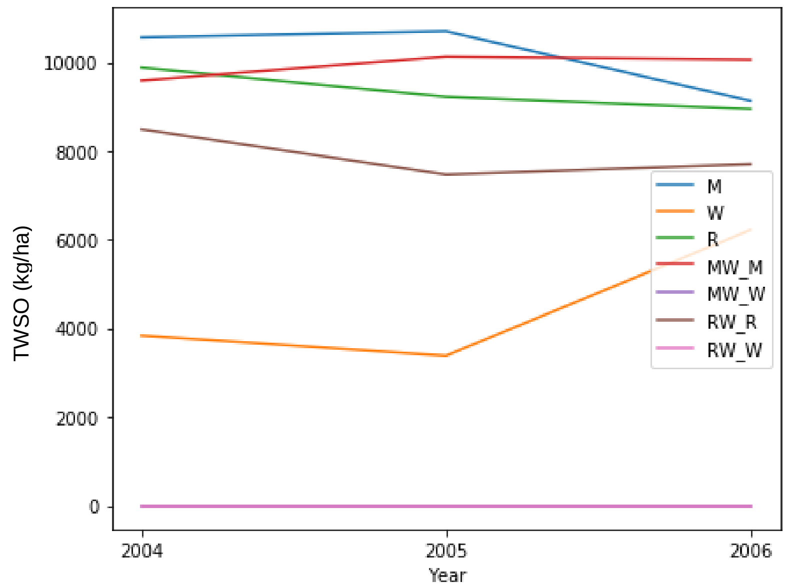
One important parameter in the agromanagement is the start date of the crop simulation. Unlike the WCC, the PCSE does not have the '*variable sowing date*' option, a feature that finds the best time for sowing based from the soil characteristics and weather. Since the benchmark study only mentioned the month and did not specifically indicate the day of sowing, a plausible sowing date must be determined. This was achieved by finding the optimal day for the specified sowing month for each year as shown in Fig. 14.

```
Initialize max_yield to 0
Initialize find_opt = True, to find optimal start_date

If start_date is NOT set,
      Set start_date = first day of the month
      Set num_days =  start_month's number of days
Otherwise,
      Set find_opt = False, to skip finding optimal start_date

If find_opt = True,
      for n = 0 to num_days:
            current_date = start_date + n
            Set the crop's agromanagement start_date = current_date
            Run Wofost71_PP engine using run_till_terminate()
            Fetch summary_output using get_summary_output()
            If summary_output['TWSO'] > max_yield,
                  Set max_yield = summary_output['TWSO']
                  Set optimum_start_date = current_date
                  Set optimum_summary  = summary_output
```

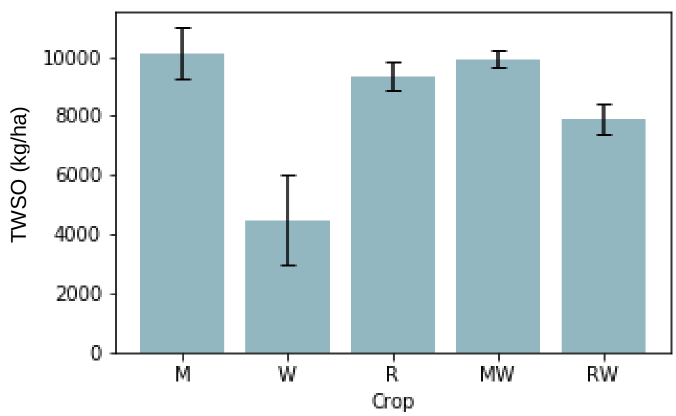
Fig. 14. Pseudocode for finding optimal start date.

The end dates were all set to the last day of the indicated harvest month of the crops. The potential yield (TWSO) alongside with the other output variables (e.g. TAGP, TWLV, TWST) of each crop rotation alternative was simulated using the *Wofost71_PP* engine. *Wofost71_PP* is an implementation of WOFOST 7.1 for potential production scenarios.

Fig. 15.a exhibits the simulated potential yield of the different crops for each year. Fig. 15.b, on the other hand, presents the average yield of the crop rotation alternatives from 2004 to 2006.



(a) Total weight of storage organ (yield) per year



(b) Mean and standard deviation of yield

Fig. 15. Simulated yield (2004-2006) using PCSE-WOFOST.

It is interesting to note that the yield of the winter wheat (MW_W and RW_W) for the MW and RW rotation are both zero. The simulation result indicates that with the provided start and end date, the crop did not reach the development stage of its storage organs. This is probable when the crop is grown primarily as cover crop and not as cash grain. Also, in [41], it was mentioned that grain crops like Maize may follow winter forage crops. This, in some way, justifies why Maize (M) and Rice (R) has a higher yield compared to the yield of having multiple crops in the rotation like MW and RW.

4.2.3 Gross Income, Energy Output, and Soil Cover Index Data Indicator Values

After simulating the yield of the crop rotation using the crop simulation model, the next goal is to utilize the simulation results for the sustainability assessment. The simulation output variables needed to derive the gross income, energy output, and soil cover index indicators were identified. Afterwards, the resulting indicator values were compared to the benchmark study.

a) Gross Income

One of the output variables of the simulation is the TWSO which represents the yield of the crop. The UN's FAO, on the other hand, provides the FAOSTAT database [52] which stores historical data of crop producer prices in various countries and regions. The gross income was calculated using the simulated average yield (TWSO) multiplied by the acquired average producer price of the crop for the simulated years. The simulated crops' annual producer price data for Italy are presented in Fig. 10.

Fig. 16 reports the obtained gross income indicator values of the alternatives. The rice (R) crop rotation returns the highest gross income while winter wheat (W) profits the lowest which is in consonance with the results of the benchmark study as shown in Fig. 17. The figure displays an error bar of the obtained gross income values of the alternatives, put side by side with the results of the benchmark study.

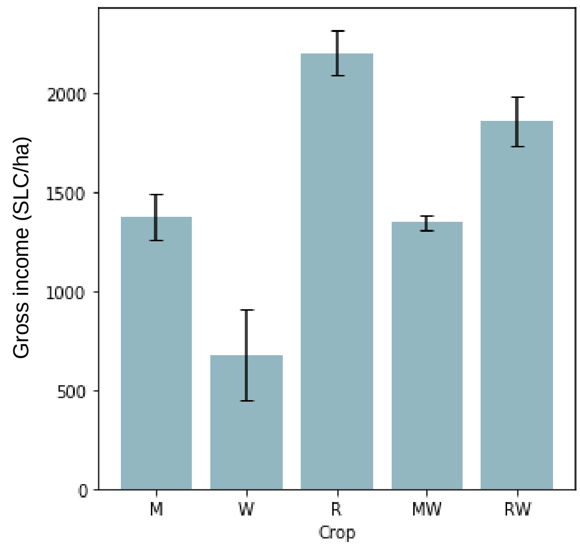


Fig. 16. Obtained gross income indicator values.

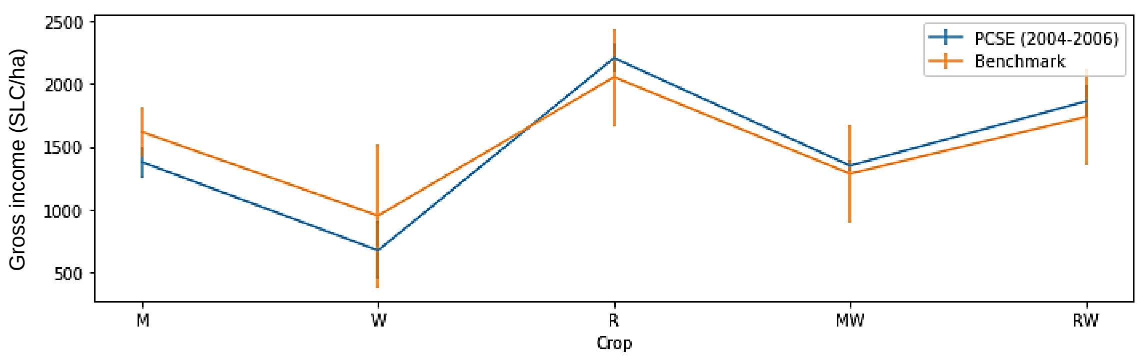


Fig. 17. Comparison of the obtained gross income (PCSE) and the benchmark study.

The root-mean-square error (RMSE) of the obtained gross income is 187.76 which can be considered relatively low for a minimum and maximum observed gross income of 951 and 2,052, respectively. The overlap and the similar propensity of the benchmark and simulated indicator values indicate the reliability of the obtained data and the methods used to acquire the indicator value.

b) Energy Output

To measure the energy output of the alternatives, the benchmark study took into account the direct energy or the calorific value of the product. It was computed by acquiring the equivalent calorific values of the dry matter of yield [55]. The reported calorific energy content of the crops' grain and straw are shown in Fig. 18.

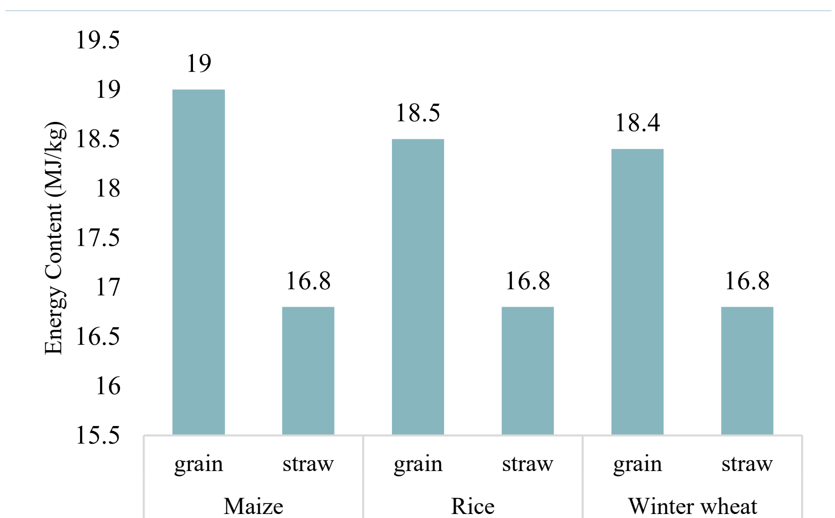
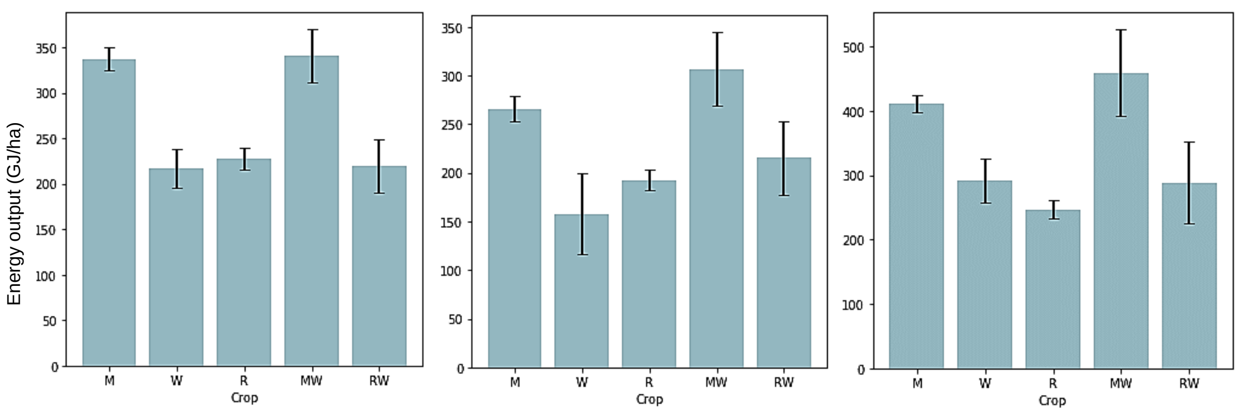


Fig. 18. Calorific energy content of crop products **[55]**.

To compute the energy content of the crop's grain, the product of TWSO and the equivalent energy content of the grain was derived. For the straw's energy content, we investigated and compared the results of using the TWST, TWLV, or both since there is limited information on the benchmark study on which part of the crop was considered for it.

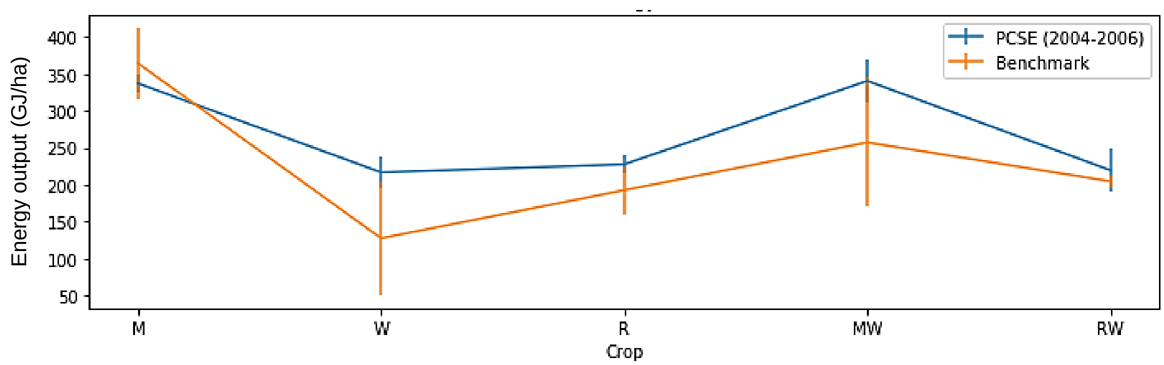
The obtained energy output indicator values of the alternatives using the TWLV, TWST, or both for the straw's combined with the grain's energy content are presented in Fig. 19. In the benchmark study, maize has the highest mean energy output while winter wheat has the lowest and the results using the TWST energy content appears to be more relevant to it.



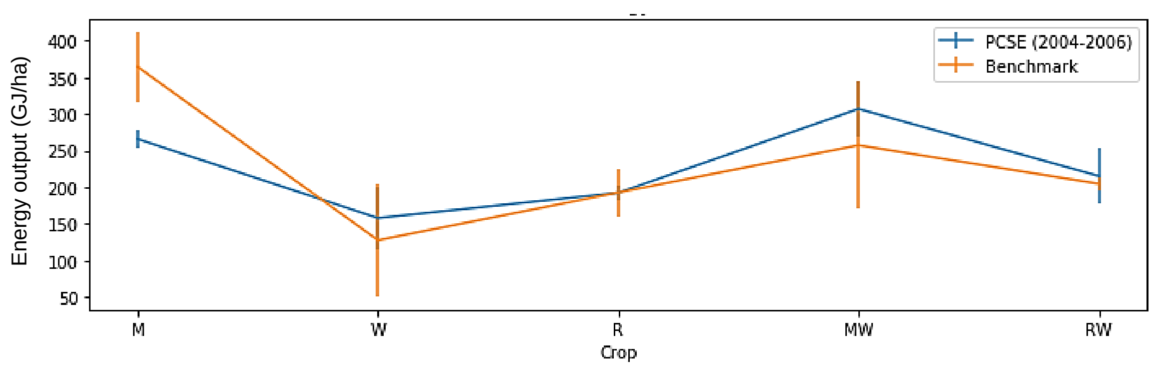
(a) TWST (b) TWLV (c) TWST and TWLV

Fig. 19. Obtained energy output indicator values using (a) TWST, (b) TWLV, and (c) both for the straw's energy content.

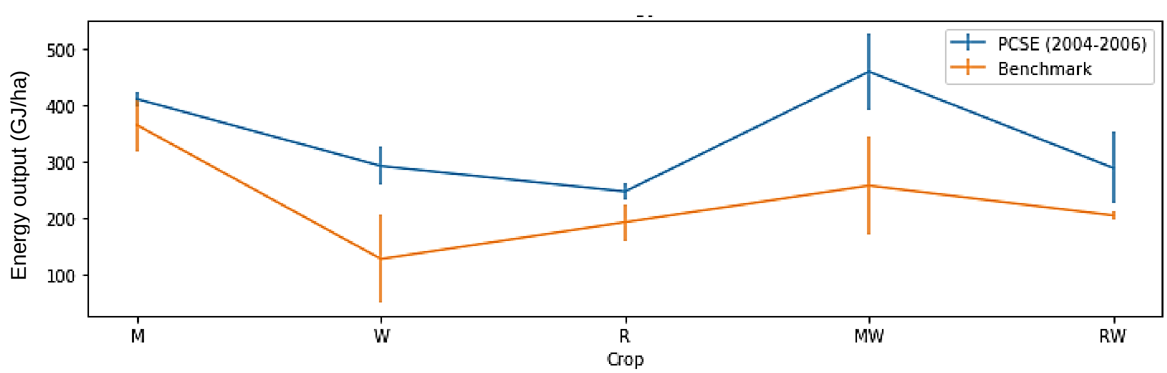
Looking at the error bar of the obtained energy output values of the alternatives compared with the results of the benchmark study in Fig. 20, it can be noted that the TWLV results are more comparable to the observed values. The resulting energy output for maize (M), however, is significantly lower than the benchmark study. Calculating the overall RMSE, the obtained energy output, when TWST, TWLV, and both are used for the straw's energy content, return an RMSE of 58.52, 51.48 and 126.48, respectively. This demonstrates that calculating the straw's energy content using the TWLV output variable would provide a better estimate of the crop's energy output based from the energy output indicator values in the benchmark study.



(a) Using TWST for the straw's energy content



(b) Using TWLV for the straw's energy content



(c) Using TWST and TWLV for the straw's energy content

Fig. 20. Comparison of the obtained energy output (PCSE) and the benchmark study.

c) Soil Cover Index

In [55], the soil cover is computed as the percentage of soil cover by crops during a year. The SCI was derived as:

$$SCI_{period} = \frac{(\sum_{i=1}^{n} SCI_{month})}{n}$$

where $\{SCI \in \mathbb{R} \,|0 \leq SCI \leq 1\}$, with 0 when the soil is bare and 1 if completely covered and *n* is the number of months. The benchmark study made assumptions that the soil is bare from sowing to crop emergence, 50% coverage from emergence to complete soil cover, and completely covered until harvest. Also, an estimate on the number of days for emergence and complete coverage has been made by the crop type.

Unlike the gross income and energy output, the needed output variable to derive the soil cover index (SCI) is not readily available in the summary output of the crop simulation. In the WOFOST 6.0 reference manual [57], the potential soil evaporation is estimated as:

$$EO_s = ETO\ e^{-k_{gb}LAI}$$

where ETO is the potential evapotranspiration rate, k_{gb} is the extinction coefficient for global radiation and *LAI* is the leaf area index. The $e^{-k_{gb}LAI}$ represents the extinction coefficient of light (*EKL*) based on the *LAI* and diffusivity of the canopy. The soil cover fraction (*SCF*) can then be derived as:

$$SCF = 1 - e^{-k_{gb}LAI}$$

In the PCSE-WOFOST model, the Evapotranspiration Class (*evapotranspiration.py*) calculates the evaporation and transpiration rates per day. The *EKL* is among the variables in the class of which the *SCF* can be derived from. *SCF* is then added as rate variable in the class which is computed as:

$$SCF = 1 - EKL$$

To aggregate the daily *SCF*, a state variable, *TSCF* was added and is derived as:

$$TSCF = \sum_{i=1}^{n} SCF_n$$

where n is the total number of simulation days (i.e. from the start date to end date set in the agromanagement). Subsequently, *TSCF* was added in the summary output variables (*SUMMARY_OUTPUT_VARS*) by modifying the *WOFOST71_PP* configuration file (*WOFOST71_PP.conf*). Finally, the *SCI* was computed as $SCI = \frac{TSCF}{n}$, where *n* is the total number of days. The obtained *SCI* indicator values of the alternatives are shown in Fig. 21. The maize and wheat (MW) crop rotation returns the highest soil cover index while rice (R) is the lowest which corresponds to the results of the benchmark study.

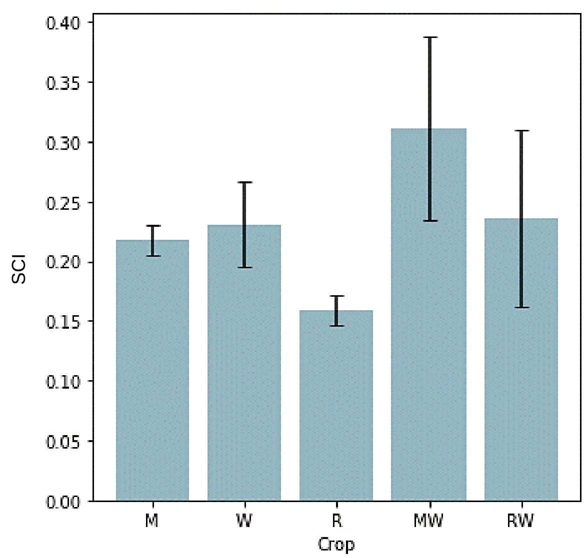


Fig. 21. Obtained SCI indicator values.

The error bar in Fig. 22 demonstrates that there is a significant difference between the obtained SCI indicator values and the benchmark study indicator (RMSE = 0.175). This can be due to the large estimate of the benchmark study on the soil coverage from emergence to complete soil cover (50%). A comparable pattern, nonetheless, is apparent which denotes the reliability of the method used to derive the indicator values. The comparison also supports the validity of the outcome as pertains to evaluating the performance of the alternatives with respect to soil cover index. However, the results accuracy needs fine-tuning by a factor of 0.55.

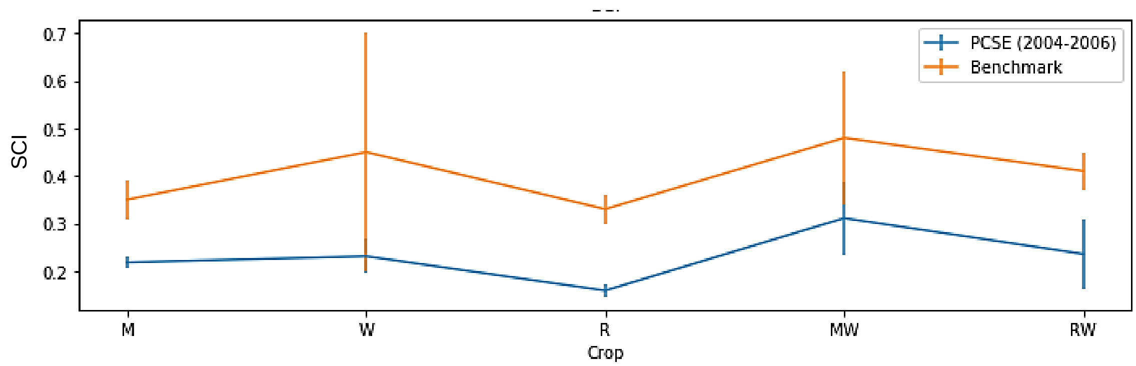


Fig. 22. Comparison of the obtained SCI (PCSE) and the benchmark study.

CHAPTER 5
INTEGRATION OF AHP AND PCSE FOR A MULTI-CRITERIA AND DYNAMIC SUSTAINABILITY ASSESSMENT

In Chapter 3, we used AHP to assess the sustainability of crop rotation alternatives to address the multi-criteria aspect of sustainability. Thereafter, we investigated the utilization of WOFOST crop simulation model to simulate the crop growth and as a dynamic source of input variables for the sustainability assessment of alternatives in Chapter 4. In this chapter, we examine the integration of a crop simulation model and AHP as an approach for a dynamic and multi-criteria sustainability assessment of crop rotation alternatives.

5.1 Integration of a Crop Model and the AHP Method

To provide a dynamic and multi-criteria sustainability assessment of crop rotation alternatives, we sought to examine the integration of a crop model and the AHP method. First, we assessed the applicability of the AHP method addressing the multiple criteria of sustainability and the diverse preferences of smallholder farmers as presented in Chapter 3. In Chapter 4, we investigated the utilization of WOFOST crop simulation model using the Python Crop Simulation Environment (PCSE) to simulate the crop growth of alternatives. To integrate the PCSE-WOFOST model with the AHP model, the Python and R interface were set up and the PCSE-WOFOST's simulation results were exported as input data for the AHP model. To test the integration, an experiment was conducted using the crop rotation alternatives and the sustainability indicators identified in Chapter 4.

5.1.1 Set up Python and R interface

One of the known and verified AHP implementations in the literature is the AHP package in R which was developed by Christoph Glur [58, 59]. Since PCSE-WOFOST was developed in Python, we have to have an interface between both languages to integrate AHP and PCSE. To do so, the RPy2 package was installed in the PCSE environment. The RPy project is focused on providing simple and robust access to R from within Python to benefit from the libraries of R while working in Python [60]. The package can be downloaded from https://pypi.org/project/rpy2/ and installed in the PCSE environment using the *pip* package installer.

5.1.2 Set AHP's Input Data Using PCSE-WOFOST's Simulation Results

After setting up the interface between the AHP package and the PCSE package using RPy2, the transfer of data from PCSE to the AHP model is the next to be taken into consideration. The AHP package requires two main inputs, the alternative and the goal. The alternative lists the crop alternatives and their attributes (i.e. their corresponding sub-criteria values). The goal, on the other hand, holds the criteria tree, pairwise preferences, and preference functions [61]. Both the alternative and the goal are structured in a YAML format and are together stored in a *.ahp* file.

5.1.3 Experiment Design

A sustainability assessment using the integrated AHP and PCSE was conducted. Fig. 23 presents the criteria, and sub-criteria employed to evaluate the alternatives and provide solution to the analysis goal. The indicators were grouped into two main criteria, the economy and environment. In the previous chapter, the gross income, energy output and soil cover index sub-criteria were defined and discussed. The values of these indicators were derived directly from the

PCSE model. On the other hand, the crop sequence indicator (CS) evaluates the suitability of the crop combinations in a crop rotation. In this experiment, the CS indicator values were acquired from [35] since the crop simulation model is not capable of assessing the suitability of the crop rotations. The CS indicator values can be located at Appendix A.3. Moreover, the crop rotation alternatives evaluated are maize (M), maize and winter wheat (MW), rice (R), rice and winter wheat (RW), and winter wheat (W).

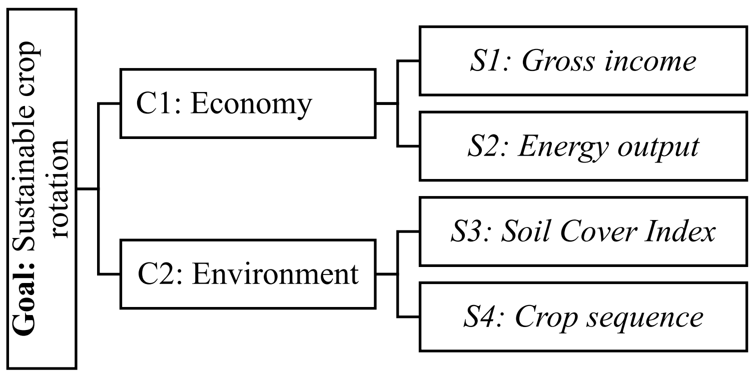


Fig. 23. Goal and decision criteria.

5.2 Multi-criteria and Dynamic Sustainability Assessment of Alternatives using the PCSE and AHP Integration

The following sections present the results of the PCSE and AHP integration to provide a multi-criteria and dynamic sustainability assessment.

5.2.1 PCSE and AHP Integration

Fig. 24 demonstrates the system architecture of the PCSE and the AHP integration. The PCSE-AHP integrator acts as intermediary between the PCSE and AHP. It provides the required input variables of the PCSE-WOFOST. The PCSE simulates the growth and yield of the crop rotation alternatives. The PCSE model then returns the output variables (TWSO, TWLV and TSCF) and based from these results, the derived indicator values are given, where:

$$Gross\ ncome = f\ (TWSO)$$

$$Energy\ output = f\ (TWSO, TWLV)$$

$$Soil\ cover\ index = f\ (TSCF)$$

Using the derived indicator values, the PCSE-AHP integrator thereafter structures the alternative and the goal of the AHP model into a YAML format and saves it as *.ahp* file. The *.ahp* file is subsequently passed to the R AHP package through the RPy2 package. Finally, the AHP model returns the corresponding priority values of the alternatives. The activity diagram in Fig. 25 displays the flow of operation of the integration of PCSE-AHP to obtain a dynamic and multi-criteria sustainability assessment of the crop rotation alternatives.

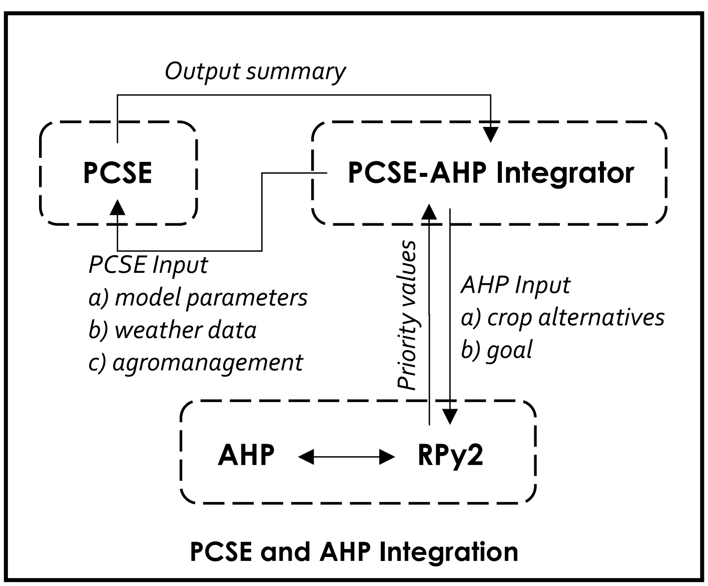


Fig. 24. PCSE and AHP integration architecture.

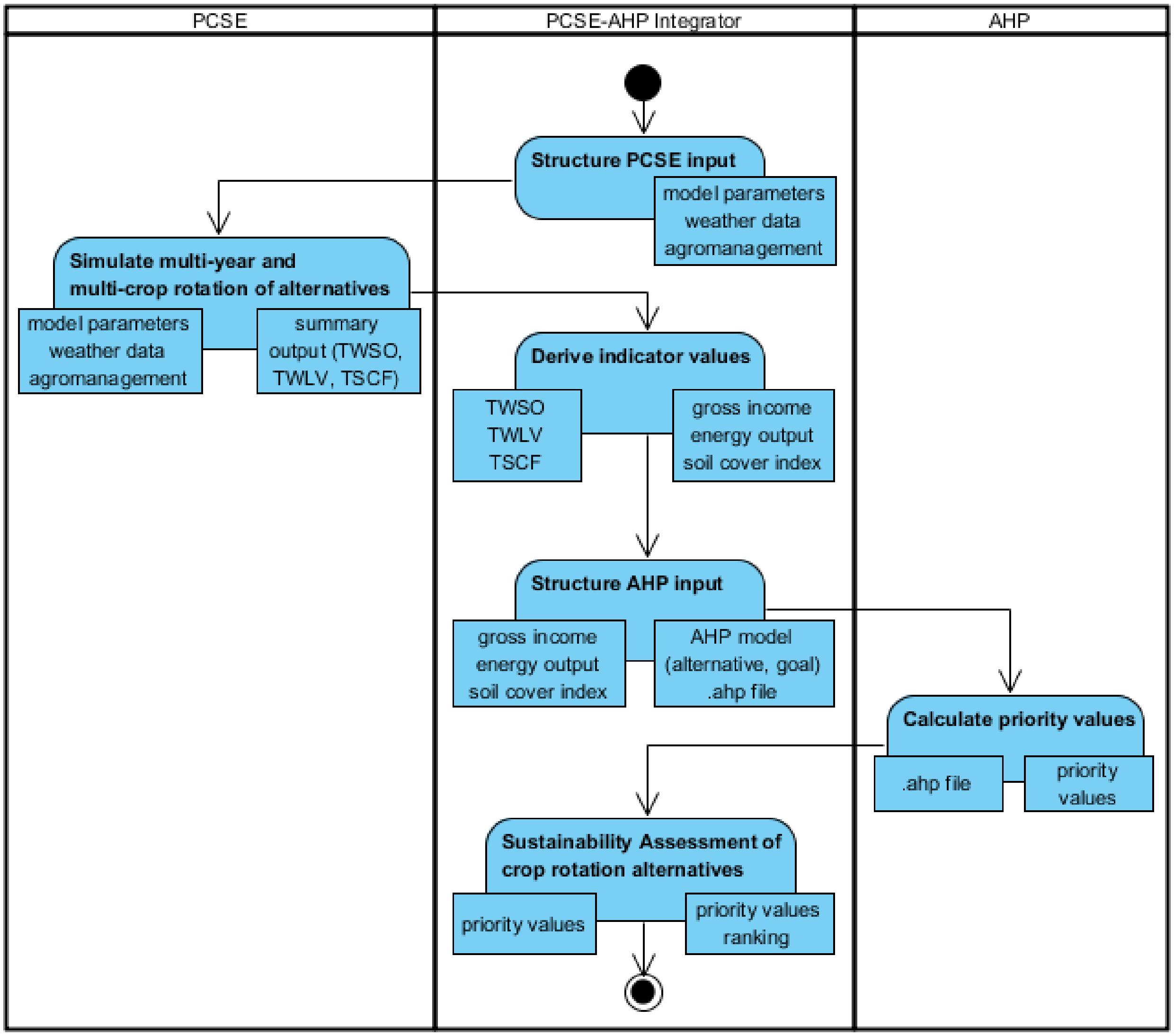


Fig. 25. Activity diagram of the PCSE-AHP integration.

5.2.2 Structuring the AHP Input Data

After simulating the yield of the crop alternatives using the PCSE-WOFOST model and deriving the indicator values by utilizing the output variable of the crop model, the input data (i.e. the alternative and goal) of the AHP model was defined.

First, the attributes (i.e. the sub-criteria values) of the alternatives were obtained using the derived indicator values and the sustainability function. The steps to acquire the sub-criteria are discussed in Section 3.1.2 (page 25). Taking into account the percent error of the obtained SCI when compared to the derived SCI of the benchmark study in Section 4.2.3 (page 48), the *smin* and *smax* threshold values of the indicator were adjusted accordingly to 0.15 and 0.21, respectively. Table 11 reports the derived mean indicator values and the computed sub-criteria values of the alternatives. These sub-criteria values were then structured into YAML format and set as the alternative portion of the AHP model. The template used, and a segment of the generated alternative section is shown in Fig. 26.

TABLE 11

SIMULATED MEAN INDICATOR VALUES AND COMPUTED SUB-CRITERIA VALUES

Criteria		M		MW		R		RW		W	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
C1	S1	1376.06	0.76	1348.18	0.70	2204.27	1.00	1859.50	1.00	675.06	0.00
	S2	265.74	1.00	306.96	1.00	192.20	0.22	215.15	0.49	157.77	0.00
C2	S3	0.22	1.00	0.31	1.00	0.16	0.14	0.24	1.00	0.23	1.00
	S4	2	0.29	4.6	0.66	1	0.14	4.1	0.59	3.5	0.50

```
#Alternatives template
Alternatives: &alternatives
{crop}:
       {criteria}: {criteria value}


#Segment of the generated alternative section
M:
    GrossIncome: 0.76
    Energy: 1.0
    SCI: 1.0
    CS: 0.29
W:
    GrossIncome: 0.0
    Energy: 0.0
    SCI: 1.0
    CS: 0.5
```

Fig. 26. Template used and a segment of the generated alternative portion.

Next, the goal portion of the AHP model which comprises the criteria, pairwise preferences, and pairwise functions, is also constructed in YAML format. Fig. 27 presents the template used, and a segment of the generated goal section.

```
#Goal Template
Goal:
  name: Crop Rotation
  description: Selection of the best crop rotation.
  author: Nisperos
  preferences:
    pairwise:
      - {criteria preferences}
  children:
    {criteria}:
      preferences:
        pairwise:
          - {sub-criteria preferences}
      children:
        {sub-criteria}:
          preferences:
            pairwiseFunction: >
              {pw[sub-criteria]}
          children: *alternatives

#Segment of the generated goal section
Goal:
  name: Crop Rotation
  description: Selection of the best crop rotation.
  author: Nisperos
  preferences:
    pairwise:
      - [Economic, Environment, 1]
  children:
    Economic:
      preferences:
        pairwise:
          - [GrossIncome, Energy Output, 1]
      children:
        GrossIncome:
          preferences:
            pairwiseFunction: >
              GrossIncome <- function(a1, a2) {
                if (a1$GrossIncome < a2$GrossIncome)
                       return (1/GrossIncome(a2, a1))
                diff = (a1$GrossIncome - a2$GrossIncome)
                PC = 8 * (diff) + 1 }
          children: *alternatives
```

Fig. 27. Template used and a segment of the generated goal portion.

The `{criteria preferences}` lists the pairwise comparison of all the criteria while the `{sub-criteria preferences}` records the pairwise comparison of the sub-criteria under a specific criterion. The `pw` variable is a dictionary containing the pairwise function of each sub-criterion. The `pw[sub-criteria]}` would list the corresponding pairwise function of the indicated sub-criterion. A discussion on how the pairwise function was derived can be found on Section 3.1.2 (page 25).

Lastly, the AHP model was created by merging the alternative and the goal sections and saving it as an *ahp* file to be accessed by the AHP package. Fig. 28 presents the program segment to access the AHP package using RPy2 and how the AHP model (*croprotation.ahp*) can be loaded in the AHP package.

```
#Import rpy2 package to access R methods
import rpy2
import rpy2.robjects as robjects
from rpy2.robjects.packages import importr

# Import R's AHP package
ahp = importr('ahp')
datatree = importr('data.tree')

#Call R AHP functions
rsystem = robjects.r['system.file']
ahpFile = rsystem("extdata", "croprotation.ahp", package="ahp")

#Load AHP file
rLoad = robjects.r['Load']
croprot = rLoad(ahpFile)
```

Fig. 28. Program segment to call AHP functions and load AHP model.

5.2.3 Multi-criteria and Dynamic Sustainability Assessment of Alternatives

Table 12 reports the derived priority values of the alternatives in the experiment. The results indicate that with respect to the given criteria and as compared to the other alternatives, the maize and wheat (MW) crop rotation is the most sustainable while continuous rice (R) is the least. It can be noted that although continuous maize (M) is not the best when it comes to the gross income (S1), it gained the highest priority value in the overall economic criteria (C1) due to its high energy output (S2). The MW crop rotation, however, outperforms the rest of the alternatives when it comes to the environmental criteria (C2).

TABLE 12

PRIORITY VALUES DERIVED USING THE CROP SIMULATION RESULTS

Criteria	w	Priority Values (%)					CR
	%	*MW*	*RW*	*M*	*W*	*R*	%
C1	50	13.0	11.7	13.7	1.5	10.2	
S1	25	3.0	8.8	3.7	0.7	8.8	3.0
S2	25	10.0	2.9	10.0	0.8	1.4	4.5
C2	50	15.5	13.1	8.4	11.0	2.2	
S3	25	6.1	6.1	6.1	6.1	0.8	0.0
S4	25	9.4	7.0	2.3	4.9	1.4	1.4
Priority	100	28.5	24.8	22.1	12.5	12.4	

Looking into the sub-criteria priority values of the crop rotation alternatives in Fig. 29, the chart depicts that the maize and wheat (MW) crop rotation, generally performs better (as compared to the other alternatives) when it comes to energy output, crop sequence indicator, and soil cover index but not in the gross income. The continuous rice (R) rotation, however, does very well in the gross income indicator, however, is not significantly sustainable with respect to energy output, crop sequence, and soil cover index. The continuous maize (M), on the other hand, generally performs competently with reference to soil cover index and energy output, as compared to the other alternatives.

These results and observations could be beneficial to smallholder farmers in their decision making. The resulting priority values can insinuate understanding of the performance of a crop rotation alternative as compared to others with respect to a particular sub-criterion and the overall criteria. The AHP model used in the experiment, however, does not encompass all the necessary indicators to assess the overall sustainability of the crop rotation alternatives. Taking into account other sustainability indicators and identifying those that could be derived using crop simulation results could be worth investigating.

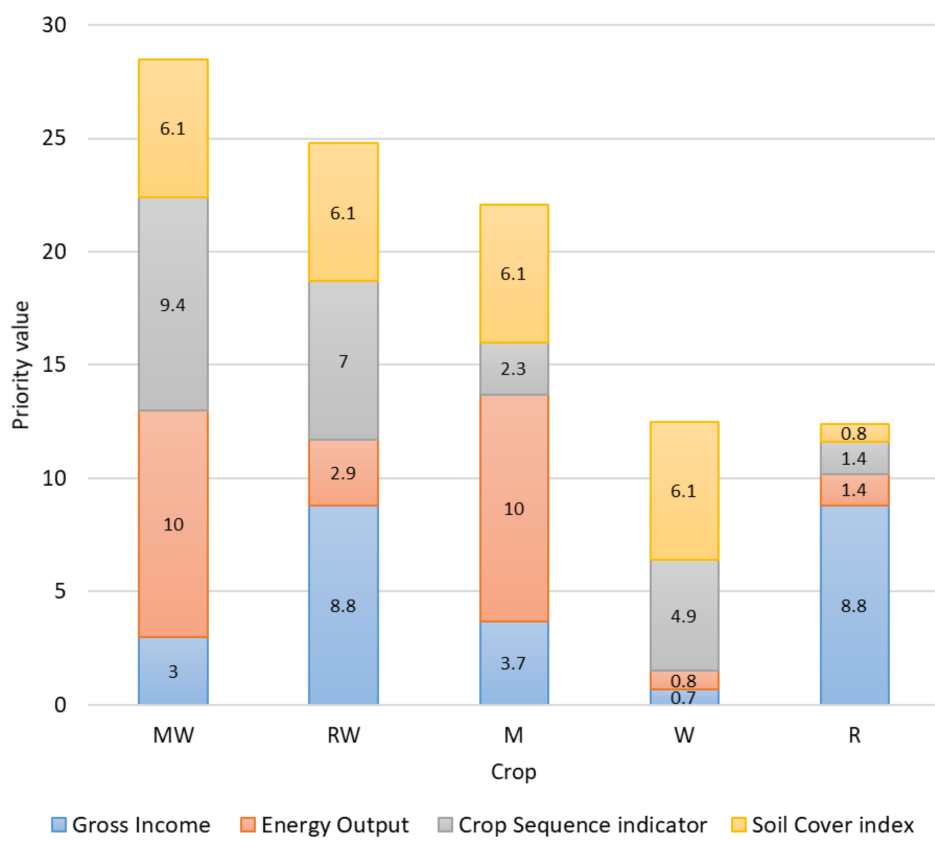


Fig. 29. Sub-criteria priority values of the alternatives (equal weight).

Table 13 presents the priority values derived when the benchmark indicator values are used in the AHP model. The results show that the variance in the observed and simulated data did not impact the overall sustainability assessment of the alternatives. This is apparent in Fig. 30 which displays the rank and overall priority values comparison of the benchmark and simulated data. Both show that maize rotated with other crops (Mo) would be the best choice, while having continuous rice is the least preferred.

TABLE 13

PRIORITY VALUES DERIVED USING BENCHMARK DATA

Criteria	w	Priority values (%)					CR
	%	*Mo*	*Ro*	*Mc*	*Ce*	*Rc*	%
C1	50	12.2	9.7	<u>17.6</u>	1.6	9.0	
S1	25	2.2	7.4	7.4	0.7	7.4	2.0
S2	25	10.0	2.3	10.2	0.9	1.6	2.6
C2	50	<u>15.9</u>	14.4	4.1	13.4	2.3	
S3	25	7.6	7.6	1.6	7.6	0.7	1.7
S4	25	8.3	6.8	2.5	5.8	1.6	0.7
Priority	100	<u>28.1</u>	24.1	21.7	15	11.3	

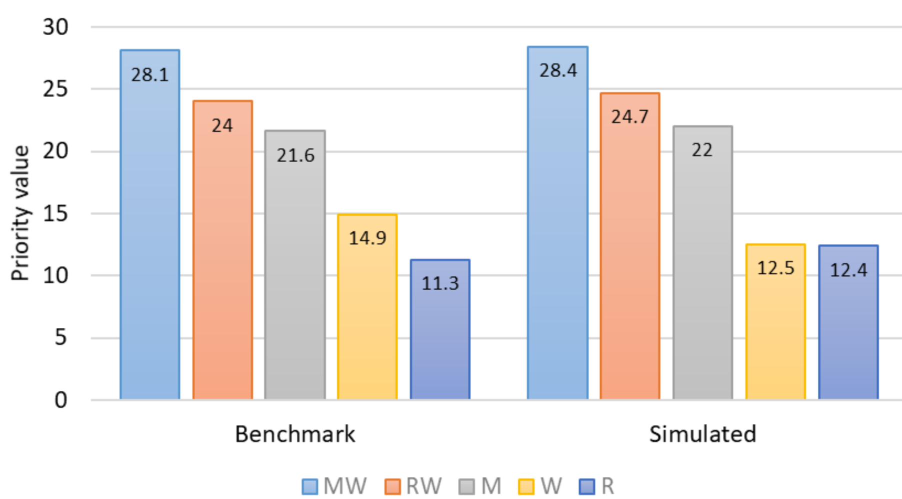


Fig. 30. Comparison of derived priority values using simulated and benchmark data.

CHAPTER 6

A SEMANTIC DATA MODEL OF COVER CROPS

Cover crops are considered an indispensable tool [33] and are an essential part of crop rotation. In essence, cover crops are short term rotations and both (cover crops and crop rotation) are recognized as good management practices [62]. Cover crops improve soil physical conditions, control soil erosion, enhance biodiversity, and restrain weeds and diseases. Also, there are several studies around the world that prove the potential of cover crops in increasing yield [33]. The selection of cover crops relies on the management goals of the farmer, which entails the benefits they want to achieve, the crop they intend to plant before and after the cover crop, the growing period and location. Information about cover crops and their respective planting specifications are thus essential in making decisions on which cover crop to plant. In this chapter, we design and build a semantic data model of cover crops using ontology to facilitate extraction, aggregation, and inferring of cover crop knowledge.

6.1 Cover Crops Concepts and Ontology Design

To develop the cover crop ontology, we examined existing cover crop selection guides in order to understand the cover crop concepts. Next, we designed and built the ontology using an ontology editor. Lastly, we verified the logical consistency of the cover crop ontology model using an OWL reasoner. Test cases were also executed to validate the asserted and inferred facts.

6.1.1 Examine Cover Crops Concepts

The *Cover Crop Planting Specification Guide* [63], *Cover Crop Chart* [64] and *Crop Sequence Calculator* [65] provide a compendium of comprehensive information about cover crops and crop sequence. The cover crops information was acquired from multiple sources including the Midwest Cover Crops Council, USDA SARE, USDA ARS and USDA NRCS plants database, and other pertinent peer-reviewed journal papers [66, 67, 68, 69]. All three sources were considered in designing and building the ontology.

6.1.2 Design and Build Ontology

An OWL ontology consists of classes, properties, and individuals. First, the ontology concepts that represent the classes (and subclasses) were identified. Next, the object and data properties and their respective characteristics (e.g. functional, transitive, symmetric, reflexive) and restrictions (e.g. quantifier restrictions – existential or universal, cardinality restrictions) were set to define the relationship between individuals and data values. Individuals are the instances of classes and the cover crops listed in [63] were transformed as individuals of the cover crop class. Moreover, the information presented in [63, 64, 65] were used to structure the class, properties and individuals of the ontology.

The ontology editor utilized to build the ontology is Protégé 5.2, a free, open-source ontology editor and framework for building intelligent systems [70, 71]. A guide to building OWL ontologies using Protégé can be found in [72]. To facilitate assertion of axioms, Cellfie, a Protégé plugin for creating OWL ontologies from spreadsheets [73], was used to import data from spreadsheet. Transformation rules were created to convert the data into axioms.

6.1.3 Verify and Validate the Cover Crop Model

Hermit, Pellet and Fact++ are among the well-known and widely used OWL reasoners [74]. All three were used to verify the logical consistency and OWL format compliance of the cover crop ontology. The Hermit, however, is the main reasoner used in executing the OWL Description Logics (OWL-DL) and SPARQL queries. To validate the asserted and inferred facts, a functional test was performed by creating test cases and comparing the query results to the expected results.

6.2 Designing, Building, Verifying, and Validating the Ontology

The following sections present the design and validation results of the cover crop ontology.

6.2.1 Designing and Building the Ontology

Cover crops are crops grown primarily to maintain soil fertility and productivity and not for harvesting. The cover crops mainly belong to the brassica, grain, grass, or legume family. Grains or grass cover crops are further classified to cool or warm season grains. Like any other crops, cover crops have specific growth properties like growth cycle, architecture, and water use.

In [33], the author outlines that to select cover crops, these steps must be considered: 1) the primary objectives of adding them to the system must be identified; 2) know the time and location to fit the cover crops into the rotation; and 3) consider how and when the cover crops are to be seeded and terminate the cover crop. From the indicated steps, it can be asserted that cover crops: 1) have specific benefits and roles in the cropping system; 2) have specific effect in the crop rotation; 3) are planted at a specific season and seeding method and have different termination method. These concepts are represented in the ontology creating classes for 1) *cover crop* as a subclass of *crop* to represent the cover crop items; 2) *benefit* and *role*, *planting season* and *termination method* to characterize the specifications of the cover crop; 3) *architecture*, *growth cycle*, *water use, seeding depth, and rate* to embody the specific crop growth and seeding properties of the cover crops; and 4) *crop rotation risk* to encompass the effect of the cover crop in a crop rotation. Fig. 31 shows the class hierarchy of the ontology as displayed by the OWLViz [75] plugin of Protégé.

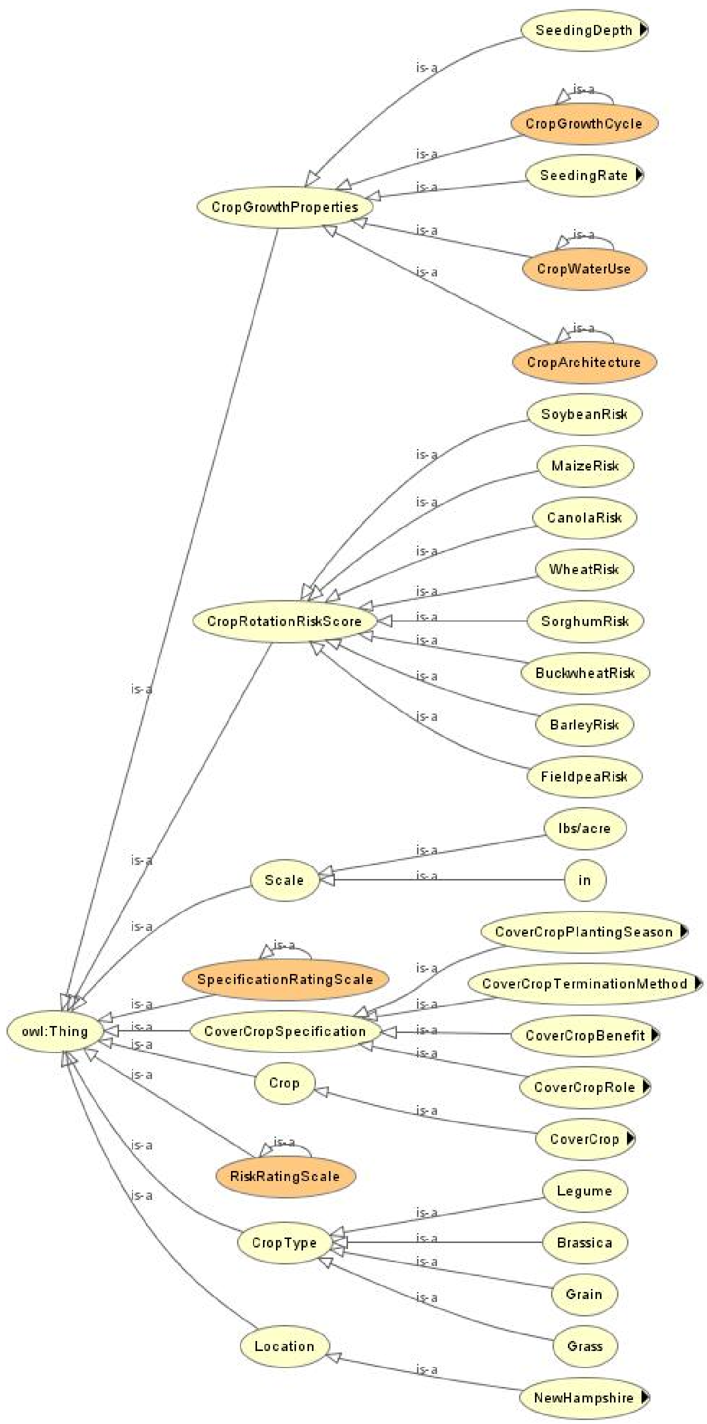


Fig. 31. Class hierarchy of the cover crop ontology.

The specification and risk rating scales are enumerated classes which list the scales of measurement used to evaluate the performance of a cover crop with respect to a particular specification and crop rotation. For specification, the individual scales are *Above Average*, *Average*, and *Below Average* while crop rotation risks are either *Very High*, *High*, *Moderate,* and *Low*. These rating scales are based from the scales used in the cover crop planting specification guide [63] of the Natural Resources Conservation Service and the cover crop chart [64] of the USDA Agricultural Research Service (USDA-ARS) where the cover crop specification and crop rotation data were acquired, respectively.

Fig. 32 displays the asserted class hierarchy of the cover crop class. The various cover crop items were asserted as a subclass of the *Cover Crop Items* class. The *Grass*, *Legume*, *Brassica* cover crops and the *Cool* and *Warm* season grains are defined classes with their necessary and sufficient criteria and any individual that satisfies the criteria will be a member of the class. The equivalent class definitions are presented in Table 14. Fig. 33, on the other hand, shows the inferred class hierarchy of the cover crop class. The cover crop items that satisfies the criteria of the defined classes now belongs to that class as well.

TABLE 14

CLASS DEFINITION OF DEFINED CLASSES

Class	Definition
BrassicaCoverCrops	$\mathrm{CoverCrop} \cap (\forall\, isAKindOf\ Brassica)$
GrassCoverCrops	$\mathrm{CoverCrop} \cap (\forall\, isAKindOf\ Grass)$
LegumeCoverCrops	$\mathrm{CoverCrop} \cap (\forall\, isAKindOf\ Legume)$
CoolSeasonGrain	$CoverCrop \cap ((\exists\, hasEarlyFallRatingOf\ SpecificationRatingScale)$ $\cup (\exists\, hasFallRatingOf\ SpecificationRatingScale)$ $\cup (\exists\, hasLateFallRatingOf\ SpecificationRatingScale)$ $\cup (\exists\, hasSpringRatingOf\ SpecificationRatingScale))$ $\cap (\forall\, isAKindOf\ Grain)$
WarmSeasonGrain	$\mathrm{CoverCrop} \cap ((\exists\, \mathrm{hasSummerRatingOf\ SpecificationRatingScale})$ $\cup\ (\exists\, \mathrm{hasEarlySummerRatingOf\ SpecificationRatingScale}))$ $\cap (\forall\, isAKindOf\ Grain)$

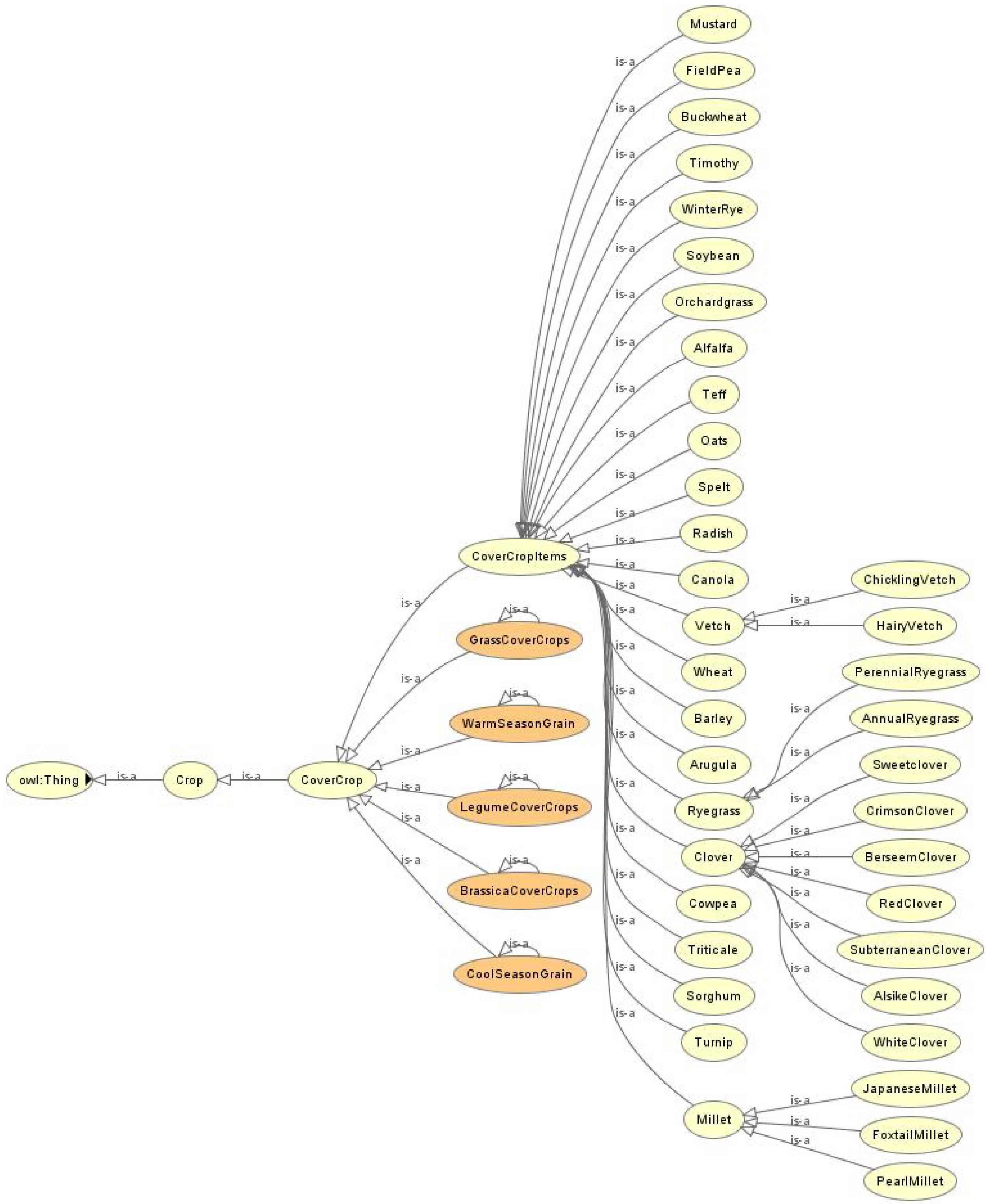


Fig. 32. Asserted class hierarchy of the cover crop class.

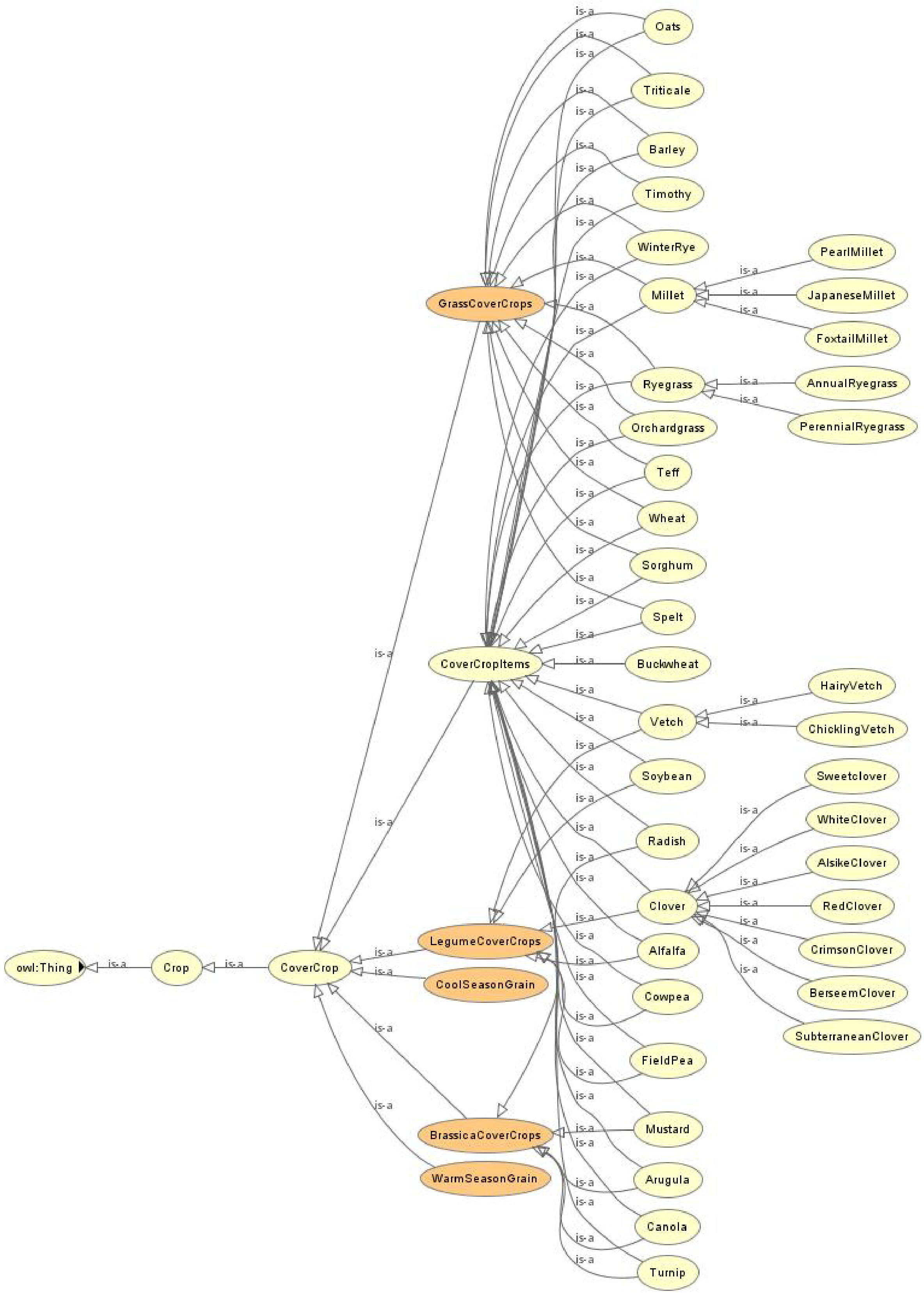


Fig. 33. Inferred class hierarchy of the cover crop class.

Another important task in ontology design is the definition of object and data properties. Object properties link two individuals while datatype properties define the relationships between individuals and data values [72]. The cover crop object and data properties are shown in Fig. 34. The *Functional* characteristic of the *hasFixNitrogenOf* object property means that an individual that *hasFixNitrogenRatingOf* property can only have one individual related to it via the property. Moreover, setting the *Domains* to ∃ hasSpecificationOf FixNitrogen would make any individual with *hasFixNitrogenRatingOf* property a member of the anonymous class ∃ hasSpecificationOf FixNitrogen. This eliminates the need to explicitly assign the property to each individual that satisfies the specification.

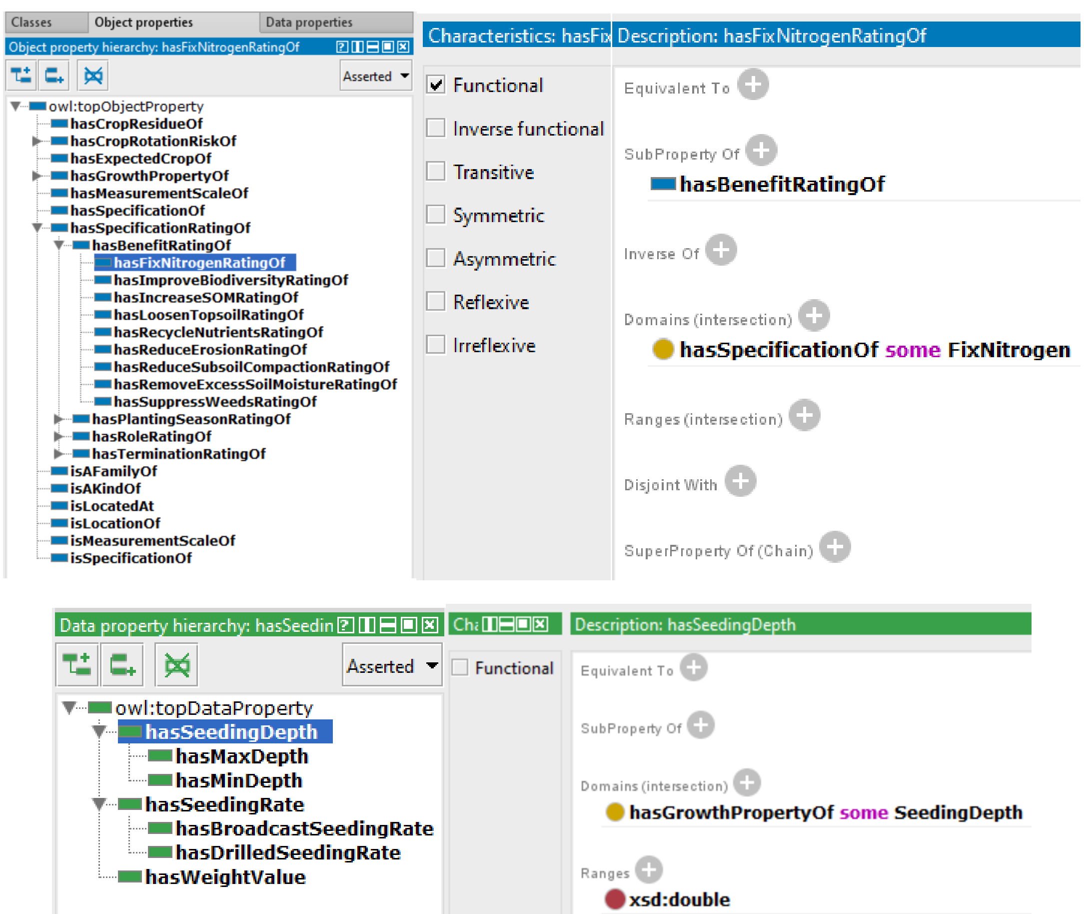


Fig. 34. Object and data properties of the ontology.

After defining the object and data properties, the individuals are created, and their properties are asserted. The object and data properties are utilized to define the properties of individuals, which are the instances of the classes. Individual properties were created from MS Excel workbook to facilitate assertion of axioms. The axioms were created using Cellfie which imports the data from the spreadsheet and transforms them into axioms using the defined transformation rules.

Appendix C.2 and C.3 lists some of the crop growth properties and crop rotation risks defined in the MS Excel workbook, below are examples of the transformation rules defined and Fig. 35 displays an example of the created individuals and property assertions. Furthermore, Appendix C.1 and C.4 present the current ontology metrics (1935 axioms, 234 classes, 45 object properties) and a snippet of the inferred axioms, respectively.

```
Crop Growth Properties Transformation Rule

Class: @C*
    SubclassOf: @B*, hasCropArchitectureOf value @E*,
                hasGrowthCycleOf  value @D*,
                hasWaterUseOf value  @F*

Crop Rotation Risks Transformation Rule

Individual: @A*
Types: @J*
Facts: hasCropResidueOf @L*,
   hasEconomicRiskOf @D*,
   hasDiseaseRiskOf @F*,
   hasWeedRiskOf @G*,
   hasInsectRiskOf @H*
```

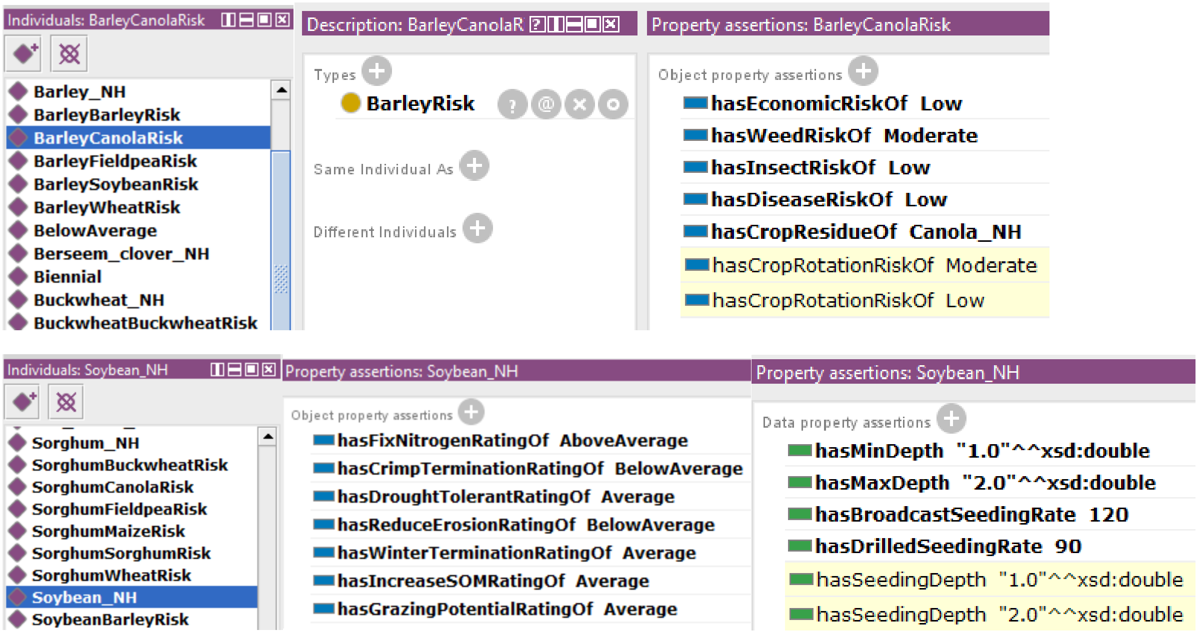


Fig. 35. Individuals and property assertions.

6.2.2 Verifying and Validating the Cover Crop Model

Using Hermit, Pellet and Fact++, the logical consistency and OWL format compliance of the cover crop ontology was verified. All reasoners were able to successfully build the class hierarchy, classify the object and data properties and compute instances for all object properties.

In the principles for design on ontologies used for knowledge sharing, Gruber [76] proposes that an ontology design must be coherent and consistent (i.e. it should sanction inferences that are consistent with the definitions and at the least the defining axioms should be logically consistent). To check the coherence and consistency of the cover crop ontology, we utilized the debug ontology feature of Protégé and the debugging session indicated that the ontology is coherent and consistent. These results verify the correctness of the cover crop ontology model with respect to logical consistency and coherence.

To validate the asserted and inferred facts, SPARQL was used to query the ontology and the query results were compared to the expected results. The test cases for the functionalities were stored in an MS Excel file and these were used in conducting the functionality test. The pseudocode of the functionality test is listed in Fig. 36 and the results in Table 15 supports the validity of the cover crop ontology results. A sample output of the functionality test is provided in Appendix C.5.

```
#Read and execute test cases
For each test case, TC:
      Read TC file
      valid = 0
      For each item in TC:
            Execute item[Query] using SPARQL
            If item [Query] Result == item[expected output]:
                  Increment valid

      TC Validity = valid/number of item in TC
```

Fig. 36. Pseudocode of functionality test.

TABLE 15

FUNCTIONALITY TEST RESULTS

Test	Correctness
SUM of item[hasSpecificationRatingOf]	100%
SUM of item[hasCropRotationRiskOf]	100%
VALUES of item[CropArchitecture]	100%
VALUES of item[CropGrowthCycle]	100%
VALUES of item[CropWaterUse]	100%
VALUES of item[SeedingDepth]	100%
VALUES of item[SeedingRate]	100%
VALUES of item[hasSpecificationOf]	100%
LIST of BrassicaCoverCrops	100%
LIST of GrassCoverCrops	100%
LIST of LegumeCoverCrops	100%
LIST of CoolSeasonGrain	100%
LIST of WarmSeasonGrain	100%

CHAPTER 7

PCSE, AHP, AND COVER CROP ONTOLOGY INTEGRATION

In the integration of AHP and PCSE in Chapter 5, one of the indicators used is the crop sequence indicator (CS) which evaluates the suitability of the crop combinations in a crop rotation. In this chapter, we examine the use of the cover crop ontology model presented in Chapter 6 as a source of knowledge for the assessment of a crop sequence and utilize it in providing the CS indicator values for the crop rotation sustainability assessment model. Thus, we integrate the PCSE, AHP, and the cover crop ontology.

7.1 Crop Sequence Evaluation and PCSE-AHP-Cover Crop Ontology Integration

To evaluate the goodness of each crop combination in a rotation, we devised a crop sequence evaluation scheme that would consider the effects, benefits, and diversity of the cover crop and crop rotation. Subsequently, the crop sequence assessment model is incorporated in the PCSE-AHP integrator to calculate the CS indicator values of the crop rotation alternatives. We then use the integrated sustainability assessment model to evaluate a selection of crop rotation alternatives.

7.1.1 Crop Sequence Evaluation

In [77, 78, 55], the effect of the previous crop on the next one was determined according to the effect (beneficial or harmful) of the previous crop on the succeeding crop, the recurrence of crops and crop diversity. Taking these factors into account, we calculated the crop sequence as:

$$CS = \frac{\sum \overline{x_h}}{n} + \frac{\sum \overline{x_b}}{m} + x_d \qquad (3)$$

where $\{CS \in \mathbb{R} \mid 1 \leq CS \leq 10\}$, x_h embodies the disease, weed, and insect effect of the previous crop on the current crop, x_b corresponds to the beneficial effect of the cover crop in the rotation, x_d evaluates the crop diversity in the rotation, *n* is the total number of crops and *m* is the number of cover crops in the crop rotation.

In the cover crop ontology, the object properties under *hasCropRotationRiskOf* and *hasBenefitRatingOf* defines the disease, weed, and insect effect of a crop sequence and the benefits of a cover crop instance, respectively. We used these properties to obtain the property assertions in the cover crop ontology and derive the values for x_h *and* x_b. The x_d, on the other hand, accounts for a number of distinct crops in the crop rotation. Table 16 lists the assigned weights to the respective benefit and crop rotation risk ratings, and crop diversity which are used to calculate the crop sequence, CS. Overall, there are nine (9) cover crop benefits asserted in the ontology. A no property assertion of a cover crop to a particular benefit implies that the cover crop is not recommended for that specific benefit.

TABLE 16

ASSIGNED WEIGHTS TO RATING AND CROP DIVERSITY

x_h		x_b		x_d	
Risk Rating	w	Benefit Rating	w	Number of crops	w
Very High	0	Above average	3	One	1
High	1	Average	2	Two	2
Moderate	2	Below Average	1	Three	3
Low	3	Not recommended	0	Four or more	4

Deriving the crop sequence indicator

Supposed that we want to evaluate the crop sequence Maize-Wheat (MW) having Wheat as a cover crop and assuming that we have the following as ontology assertions:

Assertions for WheatMaize (MW) disease, weed, and insect effect

```
WheatMaize hasDiseaseRiskOf High
WheatMaize hasWeedRiskOf High
```

Assertions for MaizeWheat (WM) disease, weed, and insect effect

```
MaizeWheat hasDiseaseRiskOf Low
MaizeWheat hasWeedRiskOf Low
```

Assertions for Wheat (W) cover crop benefits

```
Wheat hasIncreaseSOMRatingOf AboveAverage
Wheat hasLoosenTopsoilRatingOf Average
Wheat hasRecycleNutrientsRatingOf Average
Wheat hasReduceErosionRatingOf Average
Wheat hasReduceSubsoilCompactionRatingOf BelowAverage
Wheat hasRemoveExcessSoilMoistureRatingOf AboveAverage
Wheat hasSuppressWeedsRatingOf Average
```

The CS variables can be derived as:

$$\sum \overline{x_h} = \overline{x_{h_{WM}}} + \overline{x_{h_{MW}}}$$

$$= \frac{x_{h_{WM}}}{AssertionCount_{WM}} + \frac{x_{h_{MW}}}{AssertionCount_{MW}}$$

$$= \frac{3+3}{2} + \frac{1+1}{2} = 4$$

$$\sum \overline{x_b} = \overline{x_{b_W}}$$

$$= \frac{x_{b_W}}{OverallCoverCropBenefitsCount}$$

$$= \frac{3+2+2+2+1+3+2}{9} = 1.67$$

$$x_d = NumberOfDistinctCrops_{MW} = 2$$

Using Equation 3, the CS indicator can then be calculated as:

$$CS = \frac{\sum \overline{x_h}}{n} + \frac{\sum \overline{x_b}}{m} + x_d$$

$$= \frac{4}{2} + \frac{1.67}{1} + 2 = 5.67$$

7.1.2 PCSE-AHP-Cover Crop Ontology Integration

To calculate the CS indicator values of the crop rotation alternatives, we integrated the cover crop ontology into the PCSE-AHP integrator. To do so, we employed the OWLReady2 package to access the ontology in Python. OWLReady2 is a module for ontology-oriented programming in Python which allows access to OWL 2.0 ontologies and permits reasoning using HermiT [79]. The package can be downloaded from https://pypi.org/project/Owlready2/ and installed in the PCSE environment using the *pip* package installer. Information about the operation of the package can be found in [80]. Moreover, SPARQL was used to query the asserted and inferred knowledge from the cover crop ontology. A comprehensive guide on using SPARQL Query Language for RDF can be found in [81, 82].

7.2 Evaluating the Crop Sequence and Integrating the PCSE-AHP-Cover Crop ontology

This section presents the results of the crop sequence evaluation using the cover crop ontology and the integration of the crop sequence assessment model to the PCSE-AHP integrator. The output of the crop rotation assessment using the integrated sustainability assessment model is also discussed.

7.2.1 Evaluating the Crop Sequence

In the CS assessement calculation of a crop rotation, the crop sequence and the cover crops in the rotation must be specified. SPARQL was used to retrieve the asserted and inferred knowledge from the cover crop ontology and was used as input in the CS assessment calculator.

Fig. 37 shows the SPARQL query used to retrieve the crop benefit and rotation risk rating of a crop and a crop sequence, and their corresponding weight value.

The *{spec}* is a placeholder for the object property being examined, which is *hasBenefitRatingOf* for the crop benefit rating and *hasCropRotationRiskOf* for the crop rotation risk rating. The *{crop}* holds the crop sequence or cover crop being evaluated. The query returns the asserted and inferred knowledge that satisfies both the WHERE clause, which provides the basic graph pattern to match against the data graph and the FILTER, which restricts solutions to those that satisfy the filter expression [81]. The *?s, ?p*, and *?o* holds the semantic triple (subject, predicate, and object of the assertions, respectively) while *?w* takes on the equivalent weight value of the asserted object property.

```
#query to search data in the cover crop ontology
data_query = """base <http://www.semanticweb.org/nina/ontologies/2018/9/CoverCrop>
        PREFIX covercrop: <http://www.semanticweb.org/nina/ontologies/2018/9/CoverCrop#>
        SELECT ?w ?s ?p ?o
        WHERE {{ ?s ?p ?o  .
        ?p rdfs:subPropertyOf* covercrop:{spec} .
        ?o covercrop:hasWeightValue ?w .
        FILTER (regex(str(?s),'{crop}','A')) .
        }}"""

#query to search total number of specification in a specification group
n_query = """base <http://www.semanticweb.org/nina/ontologies/2018/9/CoverCrop>
        PREFIX covercrop: <http://www.semanticweb.org/nina/ontologies/2018/9/CoverCrop#>
        SELECT (COUNT(DISTINCT ?p) AS ?n)
        WHERE {{ ?p rdfs:subPropertyOf* covercrop:{spec} .
        }}"""
```

Fig. 37. SPARQL Query to retrieve data from cover crop knowledge base.

A sample output of the CS assessment is provided in Fig. 38 which shows the crop sequence and cover crop in the rotation (i.e. Maize-Wheat sequence with Wheat as a cover crop). The output shows the inferred crop sequence effect and cover crop benefits and the calculated crop sequence assessment value using Equation 3 (page 78). The output denotes that the Maize-Wheat crop rotation has a moderate crop sequence effect and has an average cover crop benefit.

The SPARQL query could be customized to account for the specific goal of a smallholder farmer. For example, if the farmer aims specifically to increase the soil organic matter or reduce subsoil compaction, then the cover crop benefit query could filter only the *hasIncreaseSOMRatingOf* or the *hasReduceSubsoilCompactionRatingOf* information. The specific goal could change the CS Assessment result and would provide a result that caters to the specific goals and preferences of the farmer.

```
CROP ROTATION:MW
COVER CROP:W

CROP SEQUENCE EFFECT (Xh)
         WheatMaize crop rotation:
                 hasDiseaseRiskOf High ( 1 )
CROP SEQUENCE EFFECT (Xh)
         MaizeWheat crop rotation:
                 hasDiseaseRiskOf Low ( 3 )
COVER CROP BENEFIT (Xb)
         Wheat cover crop:
                 hasIncreaseSOMRatingOf AboveAverage ( 3 )
                 hasLoosenTopsoilRatingOf Average ( 2 )
                 hasRecycleNutrientsRatingOf Average ( 2 )
                 hasReduceErosionRatingOf Average ( 2 )
                 hasReduceSubsoilCompactionRatingOf BelowAverage ( 1 )
                 hasRemoveExcessSoilMoistureRatingOf AboveAverage ( 3 )
                 hasSuppressWeedsRatingOf Average ( 2 )
CROP DIVERSITY (Xd)
        The crop rotation MW has crop diversity index of 2

The crop sequence indicator (CS) value of MW  crop rotation is 5.67 ( Xh = 2.0 Xb = 1.67 Xd = 2 )
```

Fig. 38. Sample output of the CS Assessment.

Using the CS Assessment calculator, we assessed the crop rotation effect of three of the crop rotations (M, W, MW) in the benchmark study in 3.1.2 (page 25). The other crop rotations in the benchmark study (RW and R) were not included in the comparison due to limitations on the crop rotation risk data of Rice (R).

Table 17 presents the comparison of the calculated CS assessment using the CS calculator and the mean indicator values assigned in the benchmark study. The CS calculator estimates that the Maize-Wheat (MW) crop rotation has the best CS effect while continuous Maize (M) returns the lowest. The results are comparable to the assessment in the benchmark study which was estimated by an expert group. This supports the reliability of the crop sequence assessment calculator on evaluating the impact of a given crop sequence and cover crop combination. More comparison tests are recommended however to further validate the assessment scheme.

TABLE 17

COMPARISON OF CS ASSESSMENT RESULT AND BENCHMARK STUDY

Crop Rotation		CS Assessment	
Crop sequence	*Cover crop*	*Benchmark Study*	*CS Calculator*
Maize (M)		2.0	1.0
Wheat (W)		3.5	2.0
Maize-Wheat (MW)	Wheat (W)	4.6	5.67

7.2.2 Integrating the PCSE-AHP-Cover Crop ontology

To employ the CS assessment calculator in deriving the CS indicator values for the crop rotation sustainability assessment model, we integrated the cover crop ontology into the PCSE-AHP integrator discussed in Chapter 5. Fig. 39 exhibits the integration architecture of the PCSE, AHP and cover crop ontology, overlaying the different components of the crop rotation sustainability assessment model. The OwlReady2 enables access to the cover crop ontology. The cover crop module takes on the crop sequence and the cover crops in the rotation as input and returns the crop sequence assessment to the PCSE-AHP-Ontology (PAO) integrator. Accordingly, the result is used as input to the crop rotation sustainability assessment's MCDA module.

The integration would allow dynamic assessment of the crop rotation alternatives by having the crop model simulate the potential crop production of the alternatives based on the provided model parameters, weather, and agromanagement data. The crop rotation and cover crop effect and benefits are also accounted for by having the cover crop ontology and using it to calculate the crop sequence impact of the crop rotation. Lastly, a multi-criteria assessment of the crop rotation alternatives is possible by the integration of the MCDA-AHP model.

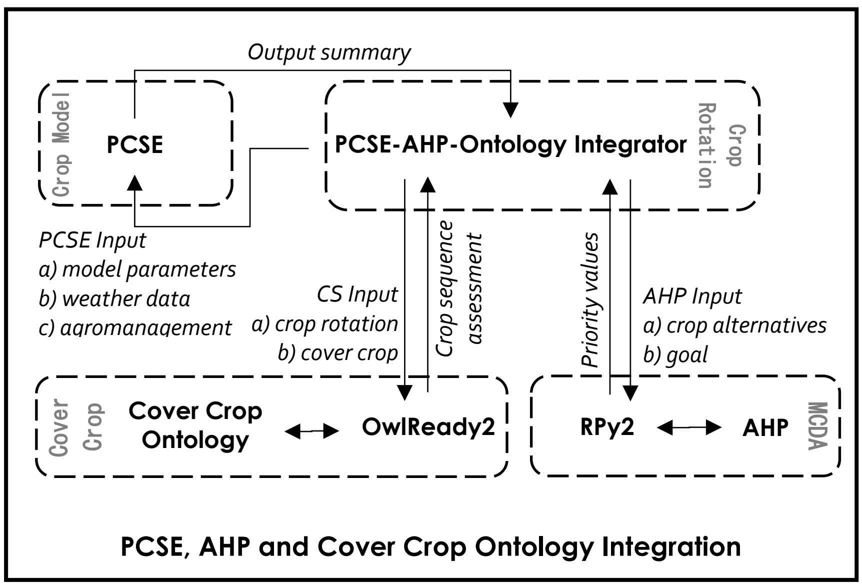


Fig. 39. PCSE, AHP, and cover crop ontology integration architecture.

Fig. 40 exhibits the flow of operation of the PCSE, AHP, and the ontology integration to obtain a dynamic and multi-criteria sustainability assessment of the crop rotation alternatives. The integrator provides the input parameters for both PCSE and Cover Crop modules. Both modules provide the parameters for the indicator values back to the integrator. Afterwhich, the integrator formats and supply the AHP model parameter. Lastly, the AHP module calculates and returns the priority values.

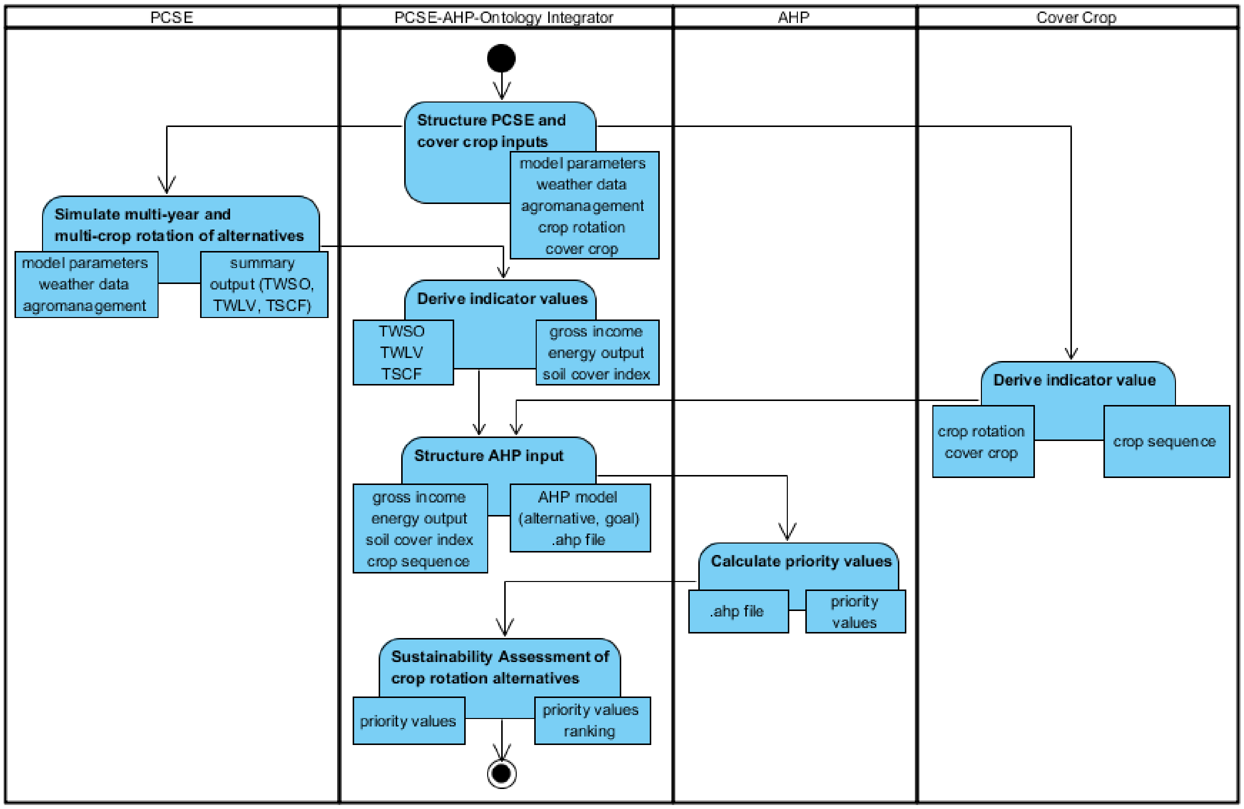


Fig. 40. Activity diagram of the PCSE-AHP-Ontology integration.

7.2.3 A Multi-criteria and Dynamic Sustainability Assessment of Crop Rotation Alternatives

Using the integrated PCSE-AHP-Cover Crop ontology, we simulate and assess the sustainability of select crop rotation alternatives. The goal and criteria are as shown in Fig. 23, with sub-criteria gross income (S1), energy output (S2), soil cover index (S3), and crop sequence indicator (S4). In the sustainability assessment of crop rotation alternatives in 5.2.3 (page 64), the results show that Maize and Wheat (MW) crop rotation is the best alternative with respect to the sustainability criteria used. In this section, we try to compare the rotation with other alternatives that could possibly substitute or complement the MW crop rotation. Aside from winter wheat, canola is another suitable cover crop because of its ability to overwinter [83]. We investigate alternating maize with canola (MC) and having an alternate of MC-MW-MC in three years. We also look into introducing another crop aside from maize by adding soybean in the rotation MW-SW-MW.

Structuring PCSE and cover crop inputs

The PCSE module requires the model parameters, weather, and agromanagement data of the crop rotation alternatives as an input. The ontology module, on the other hand, requires the crop rotation alternatives to be evaluated and the corresponding cover crops of each rotation. These inputs are needed to simulate the potential yield and assess the crop sequence effect of the alternatives. TABLE 18 summarizes the inputs used for both modules. The weather data was acquired from the NASA POWER database using 45◦N, 9◦E coordinates while the soil and crop files were from the PCSE data files. The PAO integrator structures the inputs according to the required format of the modules.

Simulating crop rotation and deriving the gross S1, S2, and S3 indicator values of alternatives

The potential yields of the alternatives are then simulated using the PCSE module. It returns the summary output of the simulation including the TWSO, TWLV, and TSCF of each alternative. Fig. 41 presents a sample output of the simulation for the MW and MC rotation. Using the simulation results, the gross income (S1), energy output (S2), and soil cover index (S3) indicator values of the alternatives are then calculated. Section 4.2.3 (page 48) discusses the methods to compute the indicators and Table 19 presents the derived S1, S2, and S3 indicator values of the crop rotation alternatives.

TABLE 18

PCSE AND COVER CROP INPUTS

Parameter	Crop rotation			
	R1: MW	R2: MC	R3: MW-SW-MW	R4: MC-MW-MC
Crop name	M: Maize W: Wheat	M: Maize C: Canola	M: Maize W: Wheat S: Soybean	M: Maize W: Wheat C: Canola
Cover Crop	Wheat	Canola	Wheat	Canola, Wheat
Start month	M: May W: Oct	M: May C: Oct	M: May W: Oct/Nov S: April	M: May W: Oct C: Oct
Start type	sowing	sowing	sowing	sowing
End date	M: Sep 30 W: Apr 20	M: Sep 30 C: Apr 20	M: Sep 30 W: Mar 20/Apr 20 S: Oct 15	M: Sep 30 W: Apr 20 C: Apr 20
End type	harvest			
Soil	EC2-Medium			
Weather	Acquired from the NASA POWER using 45˚N, 9˚E coordinates			
Year	2004-2006			

```
TWSO
    Crop: MW_M Mean: 9925.228622676463, Std: 292.0140558636336
    Crop: MW_W Mean: 0.0, Std: 0.0
    Crop: MC_M Mean: 9925.228622676463, Std: 292.0140558636336
    Crop: MC_C Mean: 0.0, Std: 0.0
TSCF
    Crop: MW_M Mean: 72.58625415687935, Std: 8.643733103650915
    Crop: MW_W Mean: 34.57565000639312, Std: 25.851076015071587
    Crop: MC_M Mean: 72.58625415687935, Std: 8.643733103650915
    Crop: MC_C Mean: 138.02850116808244, Std: 14.366974710621774
TWLV
    Crop: MW_M Mean: 3748.414230091088, Std: 885.4208957346954
    Crop: MW_W Mean: 2196.1173957417986, Std: 1719.3363972177929
    Crop: MC_M Mean: 3748.414230091088, Std: 885.4208957346954
    Crop: MC_C Mean: 5859.112903023994, Std: 2373.0631641911973
```

Fig. 41. Sample PCSE simulation output (MW and MC rotation)

TABLE 19

DERIVED INDICATOR VALUES

Criteria		R1: MW	R2: MC	R3: MW-SW-MW	R4: MC-MW-MC
		$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$
C1	S1	1348.18	1348.18	1108.74	1348.18
	S2	288.45	349.99	236.18	331.82
C2	S3	0.29	0.58	0.26	0.47
	S4	5.67	6.11	6.94	7.06

Assessing crop sequence and deriving the S4 indicator values of alternatives

The cover crop module assesses the crop sequence and derives the corresponding crop sequence indicator values of the alternatives. Section 7.1.1 (page 78) presents the methods to evaluate the crop sequence indicator of a rotation. For MW, the CS indicator is calculated as:

$$\sum \overline{x_h} = \overline{x_{h_{WM}}} + \overline{x_{h_{MW}}} = 3 + 1 = 4$$

$$\sum \overline{x_b} = \overline{x_{b_C}} = \frac{x_{b_W}}{OverallCoverCropBenefitsCount} = \frac{3+2+2+2+1+3+2}{9} = 1.67$$

$$x_d = NumberOfDistinctCrops_{MW} = 2$$

$$CS = \frac{\sum \overline{x_h}}{n} + \frac{\sum \overline{x_b}}{m} + x_d = \frac{4}{2} + \frac{1.67}{1} + 2 = 5.67$$

While for MC, the CS indicator is calculated as:

$$\sum \overline{x_h} = \overline{x_{h_{CM}}} + \overline{x_{h_{MC}}} = 3 + 3 = 6$$

$$\sum \overline{x_b} = \overline{x_{b_C}} = \frac{x_{b_C}}{OverallCoverCropBenefitsCount} = \frac{1+2+2+2+2+1}{9} = 1.11$$

$$x_d = NumberOfDistinctCrops_{MC} = 2$$

$$CS = \frac{\sum \overline{x_h}}{n} + \frac{\sum \overline{x_b}}{m} + x_d = \frac{6}{2} + \frac{1.11}{1} + 2 = 6.11$$

Table 19 presents the derived CS indicator values (S4) of the crop rotation alternatives.

Structuring AHP input

After deriving the indicator values of the alternatives, the integrator computes their corresponding sub-criteria values and structures the input for the AHP module. Section 3.1.2 (page 25) presents the steps on how to derive the sub-criteria value. The sub-criteria values are computed using Equation1, the defined sustainability function parameter values presented in Appendix A.2 and the derived indicator values. For *S4* indicator, the sustainability function parameters are S_{min} = 0, S_{opt1} = 7, and k = 1. The *S4* sub-criteria values of the alternatives are then calculated as:

$$s_{4j} = \left(\frac{\mathrm{x}_{4j} \ - 0}{7 - 0}\right)^1$$

For MW, which has an S4 indicator value, x = 5.67, its sub-criteria value for *S4* is computed as:

$$s_{41} = \left(\frac{5.67 \ - 0}{7 - 0}\right)^1 = 0.81$$

On the other hand, MC, which has an S4 indicator value x = 6.11, its sub-criteria value for *S4* is calculated as:

$$s_{42} = \left(\frac{6.11 - 0}{7 - 0}\right)^1 = 0.87$$

Similar steps are done for each alternative and for all sub-criteria. Table 20 presents the simulated indicator values ($\bar{x}$) and the computed sub-criteria values (s) of the crop rotation alternatives. Subsequently, the PAO integrator utilizes the calculated sub-criteria values as input for the AHP model and passed it on to the AHP module for comparison and computation of the priority values of the crop rotation alternatives.

TABLE 20

INDICATOR VALUES AND COMPUTED SUB-CRITERIA VALUES OF ALTERNATIVES

Criteria		R1: MW		R2: MC		R3: MW-SW-MW		R4: MC-MW-MC	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
C1	S1	1348.18	0.70	1348.18	0.70	1108.74	0.00	1348.18	0.70
	S2	288.45	1.00	349.99	1.00	236.18	0.74	331.82	1.00
C2	S3	0.29	0.60	0.58	1.00	0.26	0.46	0.47	1.00
	S4	5.67	0.81	6.11	0.87	6.94	0.99	7.06	1.00

Calculating priority values

After the integrator structures the AHP input, the AHP module compares the alternatives and computes the priority values. Section 3.1.2 (page 25) discusses the detailed steps on how the pairwise comparison is done, and the priority values are calculated. First, the pairwise comparison matrices for each sub-criterion are constructed using Equation 2 (pairwise function). For sub-criteria *S4*, we construct its pairwise matrix by comparing each alternative's corresponding S4 sub-criteria value (*R1* = 0.81, *R2* = 0.87, *R3* = 0.99, *R4* = 1.00). Comparing *R1=0.81* and *R2=0.87*, we get:

$$a_{12} = \frac{1}{1 + 8 * |s_{41} - s_{42}|} = \frac{1}{1 + 8 * |0.81 - 0.87|} = 0.68$$

and for *R1=0.58* and *R3=0* comparison, we derive,

$$a_{13} = \frac{1}{1 + 8 * |s_{41} - s_{43}|} = \frac{1}{1 + 8 * |0.81 - 0.99|} = 0.41$$

Table 21 shows the derived pairwise comparison matrix for *S4* sub-criteria. The next steps are to normalize the matrix and derive the mean of rows, and the results of these steps are presented in Table 22. The same steps are performed for each sub-criteria and the resulting weighted priority values of each alternative are aggregated to obtain the overall priority values.

TABLE 21

PAIRWISE COMPARISON MATRIX FOR SUB-CRITERIA S4 (CROP SEQUENCE)

	R1	R2	R3	R4
R1	1	0.68	0.41	0.40
R2	1.48	1	0.51	0.49
R3	2.44	1.96	1	0.93
R4	2.52	2.04	1.08	1

TABLE 22

NORMALIZED TABLE AND DERIVED PRIORITY VALUES FOR S4 (CROP SEQUENCE)

Sum of Columns (sum_k)				
	R1	R2	R3	R4
S4	7.44	5.68	3.00	2.81

↓

Normalized Matrix (a'_{jk})				
S4	R1	R2	R3	R4
R1	0.1344	0.1190	0.1366	0.1411
R2	0.1989	0.1762	0.1701	0.1743
R3	0.3280	0.3453	0.3333	0.3292
R4	0.3387	0.3594	0.3600	0.3555

↓

S4	Local Priority Value (lp_j)	Weighted Local Priority Value (p_{ij}) $w_i = 25$
R1	0.13	3.3
R2	0.18	4.5
R3	0.33	8.3
R4	0.35	8.8

Fig. 42 presents the derived priority values using the AHP module which can then be used to assess and compare the alternatives' sustainability. The result shows that the Maize-Canola (MC) and Maize-Wheat (MW) rotations have corresponding priority values with regard to gross income and energy output indicators. However, the MC outperforms MW in terms of the crop sequence and soil cover index indicators. This is due to the high risk of disease when wheat follows a maize crop as inferred in the crop sequence assessment and this risk is also emphasized in [84]. In contrast, the MC-CM crop sequence has both low disease risk which favors the crop sequence in the sustainability assessment. The lower soil cover index priority value of MW compared to MC, on the other hand, can be supported by the fact that canola is a broadleaf plant. Also, it is indicated in [85] that canola outperforms wheat on protecting the soil from erosion during its early growth.

	Weight	MCMWMC	MC	MW	MWSWMW	Inconsistency
Crop Rotation	100.0%	34.5%	30.2%	21.5%	13.7%	0.0%
Economic	50.0%	15.5%	15.5%	15.5%	3.6%	0.0%
Gross Income	25.0%	7.9%	7.9%	7.9%	1.2%	0.0%
Energy Output	25.0%	7.5%	7.5%	7.5%	2.4%	0.0%
Environment	50.0%	19.0%	14.8%	6.1%	10.1%	0.0%
Crop Sequence	25.0%	8.8%	4.5%	3.3%	8.4%	0.2%
Soil Cover index	25.0%	10.3%	10.3%	2.8%	1.7%	1.2%

Fig. 42. Priority values derived using the crop rotation assessment model (equal weights).

The derived priority values also depict that combining MC-MW-MC in the rotation outdo both MC and MO crop rotation due to a better crop sequence performance particularly on the cover crop benefits and crop diversity. For MW-SW-MW, although it has a viable crop sequence priority value, the low gross income, energy output, and soil cover index affect its overall priority value which is mainly caused by having the soybean in the rotation. Overall, the MC-MW-MC crop rotation can be regarded as the best crop rotation and MW-SW-MW as the least among the four with respect to the set criteria. All this information can be of assistance to smallholder farmers in the evaluation of their crop rotation choices.

Since the AHP model used in the experiment does not comprise all the necessary indicators to assess the sustainability of the crop rotation alternatives, it is not sufficient to conclude on the overall sustainability of the alternatives. The sub-criteria priority values, nonetheless, can help in understanding and facilitate comparisons of the crop rotation alternatives' performance with respect to the sub-criteria considered in the assessment.

CHAPTER 8

CONCLUSION AND FUTURE WORK

In this study, we sought to address the limitations on crop rotation sustainability assessment by developing a multi-criteria and dynamic sustainability assessment model that considers the economic and environmental impact of a multi-year and multi-crop rotation. We investigated the integration of a crop simulation model, multi-criteria decision analysis, and an ontology-based cover crop model as an approach for a multi-criteria and dynamic sustainability assessment of crop rotation alternatives.

8.1 Multi-criteria Sustainability Assessment using AHP

We used and investigated the applicability of Analytical Hierarchy Process, an MCDA method, 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 a benchmark study and the resulting ranking of the evaluated crop rotation alternatives are comparable regardless of the different inclinations of the stakeholder groups. This supports the validity of the pairwise function used in comparing the crop rotation alternatives. Furthermore, it strengthens the validity of the AHP method in evaluating the multiple criteria of sustainability and the diverse preferences of stakeholders.

The AHP also ranked the same top crop rotation alternative as the benchmark study's result for all stakeholder cases which demonstrates the capability of AHP to find the best alternative. Moreover, the derived priority values enable analysis of the sustainability impact of the crop rotation alternatives which, when presented aptly, can support smallholder farmers in their decision making.

8.2 Dynamic Sustainability Assessment of a Multi-year and Multi-crop Rotation using PCSE

To address the single year and single crop rotation limitation of crop rotation sustainability assessment methods, we investigated the use of PCSE as a tool to simulate the multi-year and multi-crop rotation of alternatives and examined the utilization of the simulation results for a dynamic sustainability assessment of alternatives. The gross income, energy output, and soil cover index indicator values were obtained from simulation results using the simulated total weight of storage organs and leaves, and the soil cover fraction. After which, the outcomes were validated by comparing the resulting indicator values with the indicators of the benchmark study.

The root-mean-square error (RMSE) of the obtained gross income can be considered relatively low and the overlap and the similar propensity of the benchmark and simulated indicator values indicates the reliability of the obtained data and the methods used to acquire the indicator value. When compared to the benchmark study, a comparable pattern is also apparent for both energy output and soil cover index which denotes the reliability of the methods used to derive the indicator values. The comparison also supports the validity of the simulation results as pertains to evaluating the performance of the alternatives with respect to gross income, energy output, and soil cover index.

We then examined the integration of PCSE and AHP as an approach for a dynamic and multi-criteria sustainability assessment of crop rotation alternatives. A sustainability assessment experiment involving multi-year and multi-crop rotations was conducted to test the integration. We compared the results when the simulated indicator values and when the benchmark study's indicator values are used. The resulting rank of crop alternatives when using the simulated data shows no significant difference when the benchmark study's indicator values are used. Both show the same best and least preferred crop rotation alternative. This certifies the validity of the PCSE and AHP integration output and its capability to assess the sustainability impact of a multi-year and multi-crop rotation.

Furthermore, the resulting priority values of the sustainability assessment can insinuate understanding of the performance of a crop rotation alternative as compared to others with respect to a particular sub-criterion and the overall criteria. The assessment results can be beneficial to smallholder farmers in their decision making.

8.3 A Semantic Model of the Cover Crop Concepts and Guides Using Ontology

To facilitate extraction, aggregation, and inferring of cover crop knowledge, we designed and built a semantic data model of cover crops using ontology. We examined the cover crops concepts and built an ontology using Protégé. The logical consistency and OWL format compliance of the cover crop ontology was verified using OWL reasoners. To validate the asserted and inferred facts, a functional test was performed by creating test cases and comparing the query results to the expected results.

All reasoners were able to successfully build the class hierarchy, classify the object and data properties, and compute instances for all object properties of the cover crop ontology. The ontology was also assessed as coherent and consistent. These results verify the correctness of the cover crop ontology model with respect to logical consistency and coherence. Additionally, the 100% correctness of the functionality tests supports the validity of the cover crop ontology results.

The asserted and inferred knowledge in the ontology can be utilized to guide farmers in their cover crop selection particularly.

8.4 A Multi-criteria and Dynamic Sustainability Assessment of Crop rotation Alternatives using PCSE, AHP, and Cover Crop Ontology

To evaluate the goodness of each crop combination in a rotation, we devised a crop sequence evaluation scheme that considers the effects, benefits, and diversity of the cover crop and crop rotation. The crop sequence assessment evaluates the crop rotation sequence based the inferred crop sequence effect and cover crop benefits in the cover crop ontology. Using the CS calculator, we assessed the crop rotation effect of three of the crop rotations in the benchmark study and their results are comparable. This supports the reliability of the crop sequence assessment calculator on evaluating the impact of a given crop sequence and cover crop combination.

Subsequently, we integrated the PCSE, AHP, and cover crop ontology to calculate the CS indicator values of the crop rotation alternatives using the crop sequence calculator. We then used the integrated sustainability assessment model to evaluate a selection of crop rotation alternatives. The results of the assessment model are affirmed by published studies which further supports the validity of the model and its results. Although the AHP model used in the experiment does not comprise all the necessary indicators to assess the sustainability of the crop rotation alternatives, the sub-criteria priority values, nonetheless, can help in understanding and facilitate comparison of the crop rotation alternatives’ performance with respect to the sub-criteria considered in the assessment.

Furthermore, the integration allows dynamic assessment of multi-crop and multi-year crop rotation by having the crop model simulate the potential crop production of the alternatives based on the provided model parameters, weather, and agromanagement data. The crop rotation and cover crop effect and benefits are also accounted for by having the cover crop ontology and using its asserted and inferred knowledge to calculate the crop sequence impact of the crop rotation. Finally, a multi-criteria assessment of the crop rotation alternatives is possible by the integration of the MCDA-AHP model. Altogether, the sustainability assessment model facilitates multi-criteria and dynamic sustainability assessment of multi-year and multi-crop rotation alternatives.

8.5 Future Work

The integration of the PCSE, AHP, and cover crop ontology provides a framework that allows multi-criteria and dynamic sustainability assessment of crop alternatives. The criteria of the AHP model, however, accounts for the gross income, energy output, soil cover index, and crop sequence indicators only and does not comprise all the necessary indicators to assess the overall sustainability of the crop rotation alternatives. Further study is needed to investigate the utilization of other simulation output variables in evaluating other indicators like the nutrient and water needs of crop rotation alternatives. It is also interesting to account for the production costs of the alternatives based on their seed costs, nutrient needs, and water needs. Another indicator considered in the benchmark study which was not covered in this research is the pesticide toxicity. Moreover, the design of a user-friendly interface and intuitive visualization of output is also recommended to facilitate the input of the preferences and goals of the smallholder farmers and visualization of the sustainability impact assessment of their alternatives.

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APPENDICES

APPENDIX A. DATA FROM CASTOLDI ET AL.

This appendix presents the data from Castoldi and Bechini [35] that were used in this study.

A.1 Sustainability function

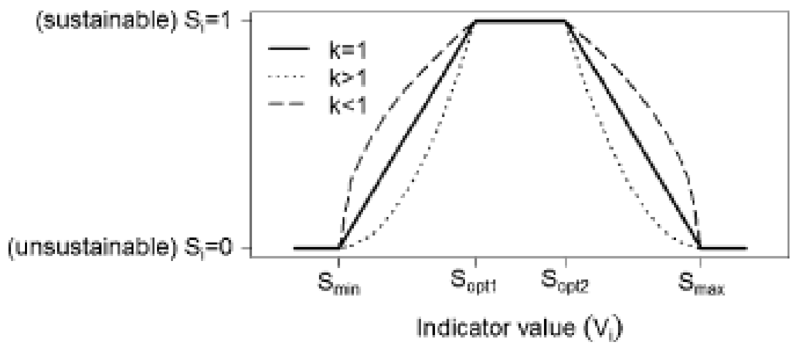


Fig. 3. A general type of function used to convert indicator values (V_i) into sustainability scores (S_i). The analytical form between S_{min} and S_{opt1} is $S_i = ((V_i - S_{min})/(S_{opt1} - S_{min}))^k$, while between S_{opt2} and S_{max} is $S_i = ((V_i - S_{max})/(S_{opt2} - S_{max}))^k$.

A.2 Parameter values used to calculate the sustainability functions

Parameters used to calculate the sustainability functions for the economic and agro-ecological indicators. See also Fig. 2 and text.

Indicator	Indicator acronym	Units	S_{min}	S_{opt1}	S_{opt2}	S_{max}	K
Economic indicators							
Variable Costs	VC	€ ha^{-1}	–	–	532	653	1.0
Gross Income	GI	€ ha^{-1}	1189	1515	–	–	0.5
Gross Margin	GM	€ ha^{-1}	749	1062	–	–	0.5
Nutrient management indicators							
Nitrogen soil surface balance	NS	kg N ha^{-1}	–20	0	50	100	0.5
Phosphorus soil surface balance	PS	kg P ha^{-1}	–79	–13	13	79	0.5
Energy management indicators							
Energy INput	EnIN	GJ ha^{-1}	–	–	23.1	27.0	1.0
Energy OUTput	EnOUT	GJ ha^{-1}	173.5	258.4	–	–	1.0
Energy Gain	EnG	GJ ha^{-1}	153.5	237.2	–	–	0.5
Pesticide toxicity indicators							
Load Index algae	LIa	TOX unit ha^{-1}	–	–	63	205	0.5
Load Index crustaceans	LIc	TOX unit ha^{-1}	–	–	0.7	1.8	0.5
Load Index fish	LIf	TOX unit ha^{-1}	–	–	0.8	2.6	0.5
Load Index rats	LIr	TOX unit ha^{-1}	–	–	1.4	2.2	0.5
Soil management indicators							
Crop Sequence indicator	CS	0–10	0	7	–	–	1.0
Soil Cover index	SC	0–1	0.33	0.39	–	–	1.0
Soil Organic Carbon Indicator	OCI	0–10	0	7	–	–	2.0

A.3 Average and standard deviation of indicators

Average and standard deviation (in parenthesis) of indicators calculated for 131 fields monitored over a 2-year period in northern Italy.

Indicator (acronym) [unit]	Crop succession (succession acronym)					
	Continuous maize (Mc)	Maize and other crops (Mo)	Continuous rice (Rc)	Rice and other crops (Ro)	Permanent meadows (PM)	Winter cereals (Ce)
	50[a]	21[a]	24[a]	3[a]	31[a]	2[a]
Economic indicators						
Variable Costs (VC) [€ ha^{-1}]	583 (108)	445 (118)	692 (45)	466 (34)	145 (17)	188 (98)
Gross Income (GI) [€ ha^{-1}]	1616 (194)	1284 (385)	2052 (389)	1736 (383)	876 (400)	951 (574)
Gross Margin (GM) [€ ha^{-1}]	1033 (222)	840 (303)	1360 (389)	1270 (414)	731 (384)	763 (476)
Nutrient management indicators						
Nitrogen soil surface balance (NS) [kg N ha^{-1}]	182 (88)	72 (47)	75 (34)	55 (9)	64 (65)	−18 (26)
Phosphorus soil surface balance (PS) [kg P ha^{-1}]	38 (52)	0 (16)	−5 (6)	−15 (3)	0 (14)	−12 (22)
Energy management indicators						
Energy INput (EnIN) [GJ ha^{-1}]	27.8 (3.8)	22.0 (6.1)	22.6 (2.5)	18.8 (2.3)	13.5 (5.1)	10.7 (7.2)
Energy OUTput (EnOUT) [GJ ha^{-1}]	364.5 (47.8)	257.3 (87.3)	192.6 (32.1)	204.6 (8.3)	156.1 (71.1)	127.4 (77.8)
Energy Gain (EnG) [GJ ha^{-1}]	336.7 (47.4)	235.3 (81.5)	169.9 (31.1)	185.8 (6)	142.6 (66.4)	116.7 (70.6)
Pesticide toxicity indicators						
Load Index algae (LIa) [TOX ha^{-1}]	108.2 (80.9)	106.5 (63.3)	259.4 (135.1)	144.5 (16.6)	0.0 (0)	0.3 (0.4)
Load Index crustaceans (LIc) [TOX ha^{-1}]	1.4 (4.1)	15.5 (37.4)	7.6 (3.4)	4.1 (0.7)	0.0 (0)	0.0 (0)
Load Index fish (LIf) [TOX ha^{-1}]	2.2 (4.2)	2.4 (4.2)	8.5 (4.3)	7.6 (2.1)	0.0 (0)	0.0 (0)
Load Index rats (LIr) [TOX ha^{-1}]	1.5 (0.4)	0.8 (0.5)	8.5 (4.1)	3.6 (1.3)	0.0 (0)	0.5 (0.7)
Soil management indicators						
Crop Sequence indicator (CS) [0–10]	2.0 (0.6)	4.6 (1.2)	1.0 (0.2)	4.1 (2.4)	10.0 (0)	3.5 (3.1)
Soil Cover index (SC) [0–1]	0.35 (0.04)	0.48 (0.14)	0.33 (0.03)	0.41 (0.04)	1.00 (0)	0.45 (0.25)
Soil Organic Carbon Indicator (OCI) [0–10]	6.3 (1.5)	4.6 (2.5)	4.3 (1.8)	2.1 (0.4)	10.0 (0)	1.4 (0.4)

[a] Number of fields monitored.

A.4 Weights assigned

Weights assigned to each indicator class (a) and to each indicator within each class (b), used in the calculation of the weighted average sustainability by class (S_c) and of the global sustainability index (S_g), respectively.

Indicator class	Indicator acronym	Equal weights	Farmers	Researchers	Agronomists	Decision-makers	Environmentalists
(a)							
Economic indicators		20	40	33	17	35	23
Nutrient management indicators		20	15	14	14	13	23
Energy management indicators		20	8	14	17	18	18
Pesticide toxicity indicators		20	13	16	11	23	13
Soil management indicators		20	25	23	40	13	22
(b)							
Economic indicators							
Variable Costs	VC	33	10	33	32	43	27
Gross Income	GI	33	10	25	15	35	47
Gross Margin	GM	33	80	42	53	23	26
Nutrient management indicators							
Nitrogen soil surface balance	NS	50	85	58	73	55	65
Phosphorus soil surface balance	PS	50	15	43	27	45	35
Energy management indicators							
Energy INput	EnIN	33	40	40	23	48	57
Energy OUTput	EnOUT	33	40	25	40	30	18
Energy Gain	EnG	33	20	36	37	23	25
Pesticide toxicity indicators							
Load Index algae	LIa	25	18	29	27	18	30
Load Index crustaceans	LIc	25	18	22	15	18	28
Load Index fish	LIf	25	23	20	18	18	25
Load Index rats	LIr	25	43	29	40	48	17
Soil management indicators							
Crop Sequence indicator	CS	33	47	33	43	40	27
Soil Cover index	SC	33	27	32	15	23	27
Soil Organic Carbon Indicator	OCI	33	27	35	42	38	47

A.5 Ranking of the crop succession types

Ranking of six crop succession types based on global sustainability index (S_g) calculated with six different sets of weights. The two tables were compiled using different methods to define S_{min} and S_{max} for economic, pesticide and energy indicators. S_{min} and S_{max} were equal in case (a) to the 1st and 3rd quartile, and in case (b) to the 10th and 90th percentile of the distribution of indicators observed. S_{min} and S_{max} are the thresholds used to define the sustainable range of the indicators; the sustainability is completely unsatisfactory in the range below S_{min} and above S_{max}. The bold type identifies the crop successions that changed in (b) compared to (a).

Succession type	Stakeholders						
	Equal weights	Farmers	Researchers	Agronomists	Decision-makers	Environmentalists	Average rank
(a)							
Maize continuous crop (Mc)	4	3	4	4	5	4	4.0
Maize and other crops (Mc)	2	4	3	2	2	3	2.7
Rice continuous crop (Rc)	6	6	6	6	6	6	6.0
Rice and other crops (Ro)	3	1	2	3	3	2	2.3
Permanent meadows (PM)	1	2	1	1	1	1	1.2
Winter cereals (Ce)	5	5	5	5	4	5	4.8
(b)							
Maize continuous crop (Mc)	4	**4**	4	4	**4**	4	4.0
Maize and other crops (Mo)	**3**	**2**	3	2	2	3	2.5
Rice continuous crop (Rc)	6	**5**	6	6	6	6	5.8
Rice and other crops (Ro)	**1**	1	**1**	3	**1**	**1**	1.3
Permanent meadows (PM)	**2**	**3**	**2**	1	**3**	**2**	2.2
Winter cereals (Ce)	5	**6**	5	5	**5**	5	5.2

APPENDIX B. AHP RESULTS

This appendix contains the resulting priority values of the AHP model for different stakeholder preferences.

B. 1 AHP Priority values result for farmers

Criteria	**w**	**Priority values** (%)					**CR**
	%	*Ro*	*Mo*	*Mc*	*Rc*	*Ce*	%
C1	40	12.4	4.0	9.6	11.4	2.4	
S1	32	10.1	2.5	8.0	10.1	1.1	2.2
S2	4	1.2	1.2	0.3	0.1	1.2	2.8
S3	4	1.2	0.3	1.2	1.2	0.1	2.9
C2	15	6.2	3.5	0.6	3.1	1.4	
S4	13	5.8	3.0	0.4	2.5	0.9	4.0
S5	2	0.5	0.5	0.2	0.5	0.5	0.0
C3	8	1.3	2.6	2.0	1.1	0.9	
S6	3	0.8	0.8	0.1	0.8	0.8	0.00
S7	3	0.3	1.2	1.3	0.2	0.1	3.70
S8	2	0.2	0.6	0.6	0.1	0.0	4.60
C4	13	0.7	2.8	3.0	0.5	5.8	
S9	5	0.2	1.8	1.4	0.2	1.8	0.40
S10	3	0.1	0.3	0.5	0.1	1.7	4.20
S11	2	0.3	0.5	0.5	0.1	0.9	2.90
S12	2	0.1	0.1	0.6	0.1	1.3	2.70
C5	25	5.7	7.6	5.1	1.9	4.6	
S13	12	3.3	4.4	1.1	0.6	2.3	1.50
S14	7	2.0	2.0	0.4	0.2	2.0	2.50
S15	7	0.4	1.3	3.6	1.0	0.3	2.70
Priority	**100**	**26.3**	**20.5**	**20.2**	**17.9**	**15.2**	

B. 2 AHP Priority values result for researchers

Criteria	w	Priority values (%)					CR
	%	Ro	Mo	Mc	Ce	Rc	%
C1	33	10.1	5.0	6.9	3.9	7.1	
S1	14	4.4	1.1	3.5	0.5	4.4	2.2
S2	11	3.2	3.2	0.9	3.2	0.3	2.8
S3	8	2.4	0.7	2.4	0.2	2.4	2.9
C2	14	4.9	3.3	0.8	2.0	3.0	
S4	8	3.7	1.9	0.3	0.6	1.6	4.0
S5	6	1.2	1.4	0.5	1.4	1.4	0.0
C3	14	2.3	4.6	3.5	1.6	1.9	
S6	6	1.4	1.4	0.2	1.4	1.4	0.0
S7	5	0.7	1.9	1.9	0.1	0.4	4.6
S8	4	0.3	1.4	1.4	0.1	0.2	3.7
C4	16	1.0	3.1	3.7	7.5	0.6	
S9	5	0.5	1.0	1.0	1.9	0.1	2.9
S10	5	0.2	1.6	1.2	1.6	0.2	0.4
S11	4	0.2	0.2	0.9	2.1	0.2	2.7
S12	3	0.1	0.4	0.6	1.9	0.1	4.2
C5	23	4.9	6.6	5.5	4.1	1.9	
S13	8	0.5	1.5	4.4	0.4	1.3	2.7
S14	8	2.1	2.9	0.7	1.5	0.4	1.5
S15	7	2.2	2.2	0.4	2.2	0.2	2.5
Priority	**100**	**23.2**	**22.6**	**20.4**	**19.2**	**14.6**	

B. 3 AHP Priority values result for agronomists

Criteria	w	Priority values (%)					CR
	%	Mo	Mc	Ro	Ce	Rc	%
C1	17	2.6	3.5	5.3	2.0	3.8	
S1	9	0.7	2.3	2.9	0.3	2.9	2.2
S2	6	1.6	0.5	1.6	1.6	0.2	2.8
S3	3	0.2	0.8	0.8	0.1	0.8	2.9
C2	14	3.4	0.7	5.5	1.6	3.0	
S4	10	2.4	0.3	4.7	0.7	2.1	4.0
S5	4	0.9	0.3	0.8	0.9	0.9	0.0
C3	17	6.1	5.4	2.5	1.4	1.9	
S6	7	2.7	2.8	0.7	0.2	0.4	3.7
S7	6	2.4	2.5	0.8	0.2	0.5	4.6
S8	4	1.0	0.1	1.0	1.0	1.0	0.0
C4	11	2.5	2.6	0.7	5.0	0.4	
S9	5	1.5	1.2	0.2	1.5	0.2	0.4
S10	3	0.7	0.7	0.3	1.3	0.1	2.9
S11	2	0.2	0.4	0.1	1.2	0.1	4.2
S12	2	0.1	0.4	0.1	1.0	0.1	2.7
C5	40	11.6	11.1	7.7	6.0	3.8	
S13	17	6.5	1.6	4.9	3.4	1.0	1.5
S14	17	3.2	9.2	1.0	0.8	2.6	2.7
S15	6	1.8	0.4	1.8	1.8	0.2	2.5
Priority	**100**	**26.0**	**23.4**	**21.7**	**16.1**	**12.9**	

B. 4 AHP Priority values result for decision-makers

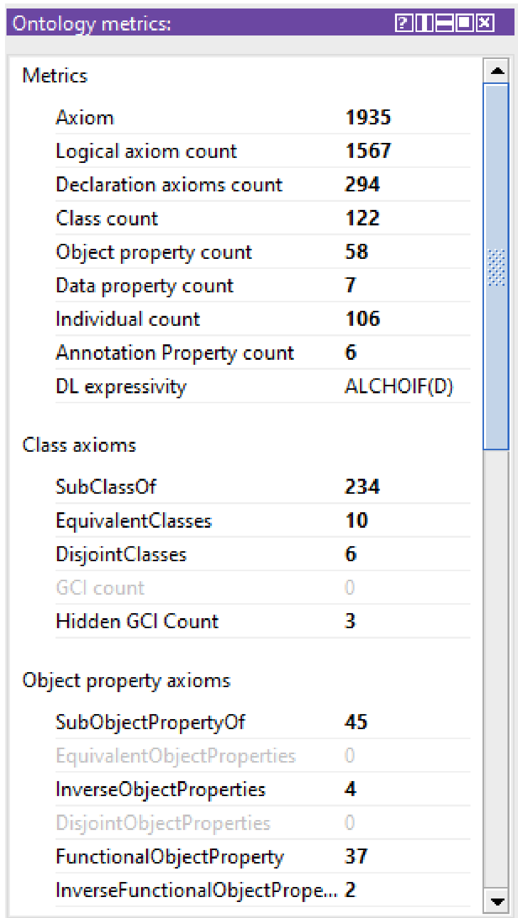
Criteria	**w**	**Priority values** (%)					**CR**
	%	Mo	Ro	Ce	Mc	Rc	%
C1	35	6.0	10.4	5.0	6.8	6.5	
S1	15	4.4	4.4	4.4	1.3	0.4	2.8
S2	12	1.0	3.6	0.3	3.6	3.6	2.9
S3	8	0.6	2.5	0.3	2.0	2.5	2.2
C2	13	3.0	4.3	1.8	0.7	2.7	
S4	7	1.6	3.2	0.5	0.2	1.4	4.0
S5	6	1.3	1.2	1.3	0.5	1.3	0.0
C3	18	5.6	3.1	2.3	3.9	2.7	
S6	8	2.0	2.0	2.0	0.2	2.0	0.0
S7	5	2.1	0.5	0.2	2.2	0.3	3.7
S8	4	1.5	0.5	0.1	1.5	0.3	4.6
C4	23	5.1	1.2	10.0	5.4	0.9	
S9	11	3.6	0.4	3.6	2.8	0.4	0.4
S10	4	0.9	0.5	1.7	0.9	0.1	2.9
S11	4	0.2	0.2	2.3	1.0	0.2	2.7
S12	4	0.5	0.2	2.4	0.7	0.2	4.2
C5	13	3.7	2.6	2.1	3.2	1.1	
S13	5	1.9	1.4	1.0	0.5	0.3	1.5
S14	5	0.9	0.3	0.2	2.6	0.7	2.7
S15	3	0.9	0.9	0.9	0.2	0.1	2.5
Priority	**100**	**23.3**	**21.6**	**21.2**	**20.1**	**13.8**	

B. 5 AHP Priority values result for environmentalists

Criteria	**w**	**Priority values** (%)					**CR**
	%	Ro	Mo	Mc	Ce	Rc	%
C1	23	7.0	3.2	5.3	2.4	5.3	NA
S1	11	3.2	0.9	3.2	0.3	3.2	2.9
S2	6	1.8	1.8	0.5	1.8	0.2	2.8
S3	6	1.9	0.5	1.5	0.2	1.9	2.2
C2	23	8.6	5.5	1.2	3.0	5.0	NA
S4	15	6.9	3.6	0.5	1.1	3.1	4.0
S5	8	1.7	1.9	0.7	1.9	1.9	0.0
C3	18	3.4	5.5	3.4	2.8	3.1	NA
S6	10	2.5	2.5	0.3	2.5	2.5	0.0
S7	5	0.6	1.7	1.8	0.1	0.4	4.6
S8	3	0.3	1.3	1.4	0.1	0.2	3.7
C4	13	0.9	2.2	3.0	6.6	0.5	NA
S9	4	0.5	0.9	0.9	1.7	0.1	2.9
S10	4	0.2	0.2	0.9	2.2	0.2	2.7
S11	3	0.1	0.4	0.6	2.0	0.1	4.2
S12	2	0.1	0.8	0.6	0.8	0.1	0.4
C5	22	4.1	6.0	6.5	3.5	2.1	NA
S13	10	0.6	2.0	5.6	0.5	1.6	2.7
S14	6	1.7	2.2	0.5	1.2	0.3	1.5
S15	6	1.8	1.8	0.4	1.8	0.2	2.5
Priority	**100**	**24.0**	**22.4**	**19.4**	**18.2**	**16.0**	

APPENDIX C. COVER CROP ONTOLOGY

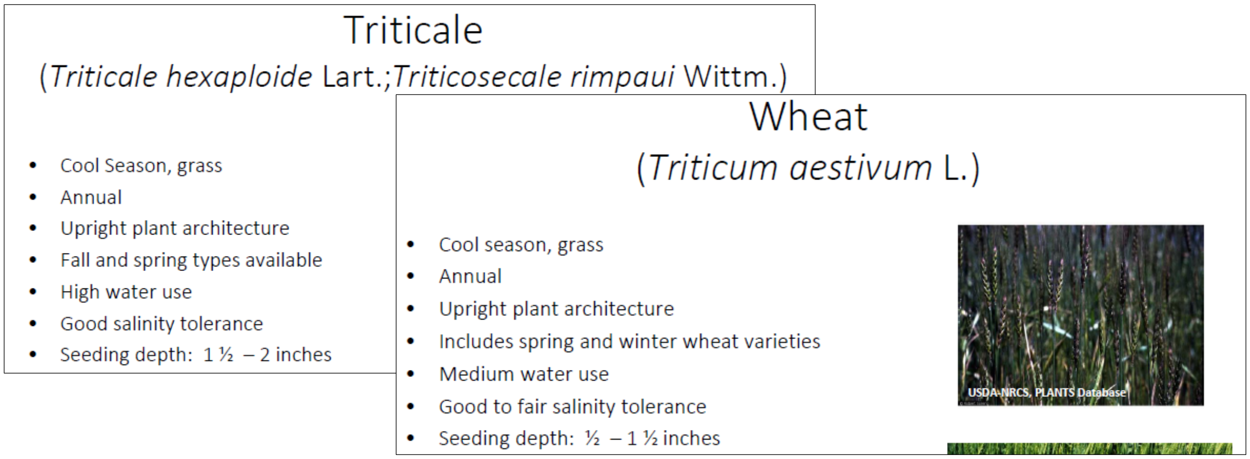
This appendix related figures and tables to the cover crop ontology model.


Ontology metrics:

Metrics	
Axiom	1935
Logical axiom count	1567
Declaration axioms count	294
Class count	122
Object property count	58
Data property count	7
Individual count	106
Annotation Property count	6
DL expressivity	ALCHOIF(D)
Class axioms	
SubClassOf	234
EquivalentClasses	10
DisjointClasses	6
GCI count	0
Hidden GCI Count	3
Object property axioms	
SubObjectPropertyOf	45
EquivalentObjectProperties	0
InverseObjectProperties	4
DisjointObjectProperties	0
FunctionalObjectProperty	37
InverseFunctionalObjectPrope...	2

C.1 Ontology metrics

C.2 Excerpts from and sample asserted crop growth properties based from [64]



Individual	Subclass	Growth Cycle	Plant Architecture	Water Use
Triticale_NH	Triticale	Annual	Upright	HighWaterUse
Spelt_NH	Spelt	Annual	Upright	
Wheat_NH	Wheat	Annual	Upright	MediumWaterUse
Barley_NH	Barley	Annual	Upright	LowWaterUse
Oats_NH	Oats	Annual	Upright	MediumWaterUse
Buckwheat_NH	Buckwheat	Annual	Upright	MediumWaterUse
Foxtail_Millet_NH	Millet	Annual	Upright	LowWaterUse
Pearl_Millet_NH	Millet	Annual	Upright	LowWaterUse
Teff_NH	Teff	Annual	Upright	MediumWaterUse
Red_clover_NH	Clover	Biennial	Upright	MediumWaterUse
Red_clover_NH	Clover	Perennial		
White_clover_NH	Clover	Perennial	Prostrate	MediumWaterUse
White_clover_NH	Clover		UprightSpreading	
Berseem_clover_NH	Clover	Annual	Upright	MediumWaterUse
Sweetclover_NH	Clover	Annual	Upright	MediumWaterUse
Sweetclover_NH	Clover	Biennial		
Crimson_clover_NH	Clover	Annual	UprightSpreading	MediumWaterUse
Alfalfa_NH	Alfalfa	Perennial	Upright	HighWaterUse
Hairy_vetch_NH	Vetch	Annual	Prostrate	MediumWaterUse
Hairy_vetch_NH	Vetch	Biennial		
Chickling_vetch_NH	Vetch	Annual	Prostrate	MediumWaterUse
Chickling_vetch_NH	Vetch	Biennial		
Field_pea_NH	FieldPea	Annual	UprightSpreading	LowWaterUse
Soybean_NH	Soybean	Annual	UprightSpreading	MediumWaterUse
Cowpea_NH	Cowpea	Annual	UprightSpreading	LowWaterUse
Radish_NH	Radish	Annual	UprightSpreading	HighWaterUse
Turnip_NH	Turnip	Biennial	UprightSpreading	HighWaterUse

C.3 Excerpt from and sample asserted crop rotation risks based from [65]

Residue Crop:	Expected Crop:	Area (ac):
Soybean - Glycine max L.	Canola - Brassica napus L.	0.0

Production and Economics:
This rotation produces 80.7% of the best rotation for this crop.
The lowest risk crop(s) following Soybean would be Dry Pea, Flax, & Soybean.

Disease:
Some diseases can damage all broadleaf crops and carry-over with the residue.
High disease risk if sclerotinia (white mold) is present in residual crop.

Weeds:
Moderate risk of weed problems. Similarity in either the crops or the planting dates.
The amounts and types of weeds depend on many factors including, but not limited to, environmental and weather variables, weed populations, and effectiveness of the previous year's weed control.

Insects:
Low risk for insect pests.
Mobile insects like grasshoppers, cutworms, and armyworms can cause problems during outbreak years.

Individual	Type	Residue	Disease Risk	Insects Risk	Weeds Risk
CanolaSoybeanRisk	CanolaRisk	Soybean_NH	High	Low	Moderate
WheatBarleyRisk	WheatRisk	Barley_NH	Moderate	Low	High
FieldpeaBarleyRisk	FieldpeaRisk	Barley_NH	Low	Low	Moderate
SoybeanBarleyRisk	SoybeanRisk	Barley_NH	Low	Moderate	Low
CanolaBarleyRisk	CanolaRisk	Barley_NH	Low	Moderate	Moderate
BuckwheatBuckwheatRisk	BuckwheatRisk	Buckwheat_NH	Very High		
SorghumBuckwheatRisk	SorghumRisk	Buckwheat_NH	Low		
FieldpeaBuckwheatRisk	FieldpeaRisk	Buckwheat_NH	Low		
CanolaBuckwheatRisk	CanolaRisk	Buckwheat_NH	High		
WheatBuckwheatRisk	WheatRisk	Buckwheat_NH	Low		
SorghumCanolaRisk	SorghumRisk	Canola_NH	Low		
FieldpeaCanolaRisk	FieldpeaRisk	Canola_NH	Moderate	Moderate	High
WheatCanolaRisk	WheatRisk	Canola_NH	Low	Low	Moderate
BarleyCanolaRisk	BarleyRisk	Canola_NH	Low	Low	Moderate
BuckwheatCanolaRisk	BuckwheatRisk	Canola_NH	High		
SoybeanCanolaRisk	SoybeanRisk	Canola_NH	High	Moderate	Moderate
CanolaCanolaRisk	CanolaRisk	Canola_NH	Very High	Moderate	High
WheatFieldpeaRisk	WheatRisk	Field pea_NH	Low	Low	Moderate
BarleyFieldpeaRisk	BarleyRisk	Field pea_NH	Low	Low	Moderate
BuckwheatFieldpeaRisk	BuckwheatRisk	Field pea_NH	Low		
SorghumFieldpeaRisk	SorghumRisk	Field pea_NH	Low		
CanolaFieldpeaRisk	CanolaRisk	Field pea_NH	High	Low	High
FieldpeaFieldpeaRisk	FieldpeaRisk	Field pea_NH	Very High	Low	High
SoybeanFieldpeaRisk	SoybeanRisk	Field pea_NH	High	Low	Moderate
BarleyWheatRisk	BarleyRisk	Wheat_NH	Moderate	Moderate	High

C.4a Sample inferred axioms

Inferred Axioms	Inferred Axioms
SoybeanCanolaRisk Type hasCropResidueOf some Crop	EquivalentClasses: RapidGrowth
owl:Nothing SubClassOf Turnip	Soybean_NH Type CoverCropItems
Hairy_vetch_NH Type hasSpecificationOf some WinterTermination	ChicklingVetch SubClassOf isLocatedAt some NewHampshire
	Turnip_NH Type hasSpecificationOf some Reseeds
Foxtail_Millet_NH Type hasSpecificationOf some	EquivalentClasses: hasSpecificationOf some
ChemicalTermination	ReduceSubsoilCompaction
Spelt_NH Type hasSpecificationOf some DroughtTolerant	CanolaSorghumRisk Type hasExpectedCropOf some Canola
Teff_NH Type hasGrowthPropertyOf some CropGrowthProperties	Timothy_NH hasPlantingSeasonRatingOf AboveAverage
BerseemClover SubClassOf CoverCrop	hasMaxDepth Range: xsd:double
White_clover_NH Type CoverCrop	hasSpecificationOf some FallSeason SubClassOf
Pearl_Millet_NH Type Crop	hasSpecificationOf some FallSeason
Wheat_NH Type hasWaterUseOf value MediumWaterUse	isAKindOf only
White_clover_NH Type hasSpecificationOf some	(Grain and Grass) SubClassOf isAKindOf only
CoverCropPlantingSeason	(Grain and Grass)
Sorghum_NH hasRoleRatingOf BelowAverage	EquivalentClasses: Alfalfa
Chickling_vetch_NH Type hasWaterUseOf value MediumWaterUse	Timothy_NH hasSeedingRate 15
	Soybean_NH hasGrowthCycleOf Annual
SoybeanFieldpeaRisk Type hasInsectRiskOf some RiskRatingScale	SoybeanBarleyRisk Type hasInsectRiskOf some RiskRatingScale
	Teff_NH Type hasSpecificationOf some CompanionCrop
FieldpeaBuckwheatRisk hasCropRotationRiskOf High	Canola_NH hasTerminationRatingOf Average
FieldpeaMaizeRisk Type hasWeedRiskOf some RiskRatingScale	owl:Nothing SubClassOf lbs/acre
Berseem_clover_NH Type hasSpecificationOf some	Barley SubClassOf hasGrowthPropertyOf some
CoverCropPlantingSeason	CropGrowthProperties
Radish_NH hasSpecificationRatingOf AboveAverage	BuckwheatMaizeRisk Type hasDiseaseRiskOf some
EquivalentProperties: hasLoosenTopsoilRatingOf	RiskRatingScale
FieldpeaBarleyRisk Type hasExpectedCropOf some FieldPea	Buckwheat_NH Type isAKindOf only
Alfalfa_NH hasSpecificationRatingOf Average	(Buckwheat and Grain)
hasSpringRatingOf SubPropertyOf: hasSpringRatingOf	hasMowTerminationRatingOf Domain hasSpecificationOf some
Pearl_Millet_NH Type hasSummerRatingOf some	CoverCropSpecification
SpecificationRatingScale	Sweetclover SubClassOf CoverCrop
FieldpeaCanolaRisk Type CropRotationRiskScore	EquivalentClasses: CropGrowthCycle
EquivalentClasses: Turnip	Sweetclover_NH hasPlantingSeasonRatingOf BelowAverage
CropArchitecture SubClassOf {Prostrate , Upright ,	Crimson_clover_NH Type hasSpecificationOf some
UprightSpreading}	GraizingPotential
Teff SubClassOf owl:Thing	hasBroadcastSeedingRate Domain hasGrowthPropertyOf some
EquivalentClasses: ImproveBiodiversity	SeedingRate
Orchardgrass SubClassOf isLocatedAt some NewHampshire	Red_clover_NH Type hasGrowthPropertyOf some
Triticale_NH hasSeedingRate 110	CropGrowthProperties
Oats_NH Type CoverCrop	Wheat_NH Type hasSpecificationOf some
owl:Nothing SubClassOf BroadcastInterseed	ReduceSubsoilCompaction
Subterranean_clover_NH hasBenefitRatingOf BelowAverage	ConnecticutRiverValley SubClassOf Location
BuckwheatFieldpeaRisk Type hasExpectedCropOf some	Cowpea_NH hasSeedingDepth "0.75"^^xsd:double
Buckwheat	Fieldpea_NH hasSpecificationRatingOf AboveAverage
Berseem_clover_NH hasBenefitRatingOf Average	Triticale_NH hasPlantingSeasonRatingOf AboveAverage
SameIndividual: CanolaBarleyRisk	BuckwheatBuckwheatRisk Type hasExpectedCropOf some
Fieldpea_NH hasCropArchitectureOf UprightSpreading	Buckwheat
Red_clover_NH Type hasSpecificationOf some LoosenTopsoil	Wheat_NH hasWaterUseOf MediumWaterUse
Oats_NH hasRoleRatingOf BelowAverage	MaizeFieldpeaRisk Type hasDiseaseRiskOf some RiskRatingScale
DrilledSeedingRate SubClassOf CropGrowthProperties	
hasGrowthPropertyOf some SeedingRate SubClassOf	Mustard_NH hasWaterUseOf LowWaterUse
hasGrowthPropertyOf some CropGrowthProperties	SummerSeason SubClassOf SummerSeason
White_clover_NH hasSeedingRate 12	CoverCropTerminationMethod SubClassOf isSpecificationOf some
Japanese_Millet_NH Type CoverCropItems	CoverCrop
Alsike_clover_NH Type Crop	WarmSeasonGrain SubClassOf (hasSummerRatingOf some
Timothy_NH Type hasSpecificationOf some Reseeds	SpecificationRatingScale) and (isAKindOf some Grain)
Pearl_Millet_NH Type hasWaterUseOf value LowWaterUse	Pearl_Millet_NH hasGrowthPropertyOf Upright
Turnip_NH Type hasSpecificationOf some RapidGrowth	Hairy_vetch_NH Type hasSpecificationOf some ImproveBiodiversity
Teff_NH Type hasSpecificationOf some CoverCropRole	MaizeSorghumRisk Type hasWeedRiskOf some RiskRatingScale

C.4b Sample inferred axioms

Inferred Axioms	Inferred Axioms
Pearl_Millet_NH Type isAKindOf only (Grain and Grass) Timothy_NH Type hasSpecificationOf some CoverCropRole SorghumRisk SubClassOf hasDiseaseRiskOf some RiskRatingScale SoybeanBarleyRisk hasCropRotationRiskOf Low EquivalentClasses: Reseeds EquivalentClasses: BrassicaCoverCrops GraizingPotential SubClassOf CoverCropSpecification CoverCropItems SubClassOf owl:Thing Red_clover_NH Type CoverCropItems owl:Nothing SubClassOf GrassCoverCrops Sweetclover_NH Type hasGrowthCycleOf value Biennial Radish_NH hasGrowthPropertyOf Annual Alsike_clover_NH hasSeedingDepth "0.5"^^xsd:double Canola_NH Type hasSpecificationOf some ChemicalTermination Timothy_NH hasSeedingRate 10 hasExpectedCropOf some Sorghum SubClassOf hasExpectedCropOf some Crop Sorghum_NH Type hasGrowthPropertyOf some SeedingDepth EquivalentClasses: Radish owl:Nothing SubClassOf CoolSeasonGrain Radish_NH hasBenefitRatingOf BelowAverage MaizeCanolaRisk Type hasExpectedCropOf some Crop Sorghum_NH hasPlantingSeasonRatingOf AboveAverage SoybeanWheatRisk Type hasInsectRiskOf some RiskRatingScale Timothy_NH Type hasSpecificationOf some RemoveExcessSoilMoisture Spelt_NH hasTerminationRatingOf Average Crimson_clover_NH hasSpecificationRatingOf AboveAverage Wheat_NH hasBenefitRatingOf AboveAverage EquivalentProperties: hasChemicalTerminationRatingOf Sorghum_NH Type Crop Turnip_NH hasTerminationRatingOf BelowAverage Hairy_vetch_NH hasRoleRatingOf BelowAverage Winter_Rye_NH Type CoverCrop CoverCrop and ((hasSummerRatingOf some SpecificationRatingScale) and (isAKindOf some Grain)) SubClassOf hasGrowthPropertyOf some CropGrowthProperties HighWaterUse Type CropGrowthProperties Radish_NH hasWaterUseOf HighWaterUse MaizeSorghumRisk Type hasExpectedCropOf some Crop FieldpeaCanolaRisk Type hasExpectedCropOf some FieldPea WheatCanolaRisk Type hasExpectedCropOf some Wheat EquivalentClasses: LegumeCoverCrops Prostrate Type CropGrowthProperties Red_clover_NH Type hasSpringRatingOf some SpecificationRatingScale PerennialRyegrass SubClassOf isLocatedAt some NewHampshire Chickling_vetch_NH hasGrowthPropertyOf Annual hasFrostTerminationRatingOf SubPropertyOf: hasFrostTerminationRatingOf Turnip SubClassOf isLocatedAt some NewHampshire Barley_NH Type hasWaterUseOf value LowWaterUse EquivalentClasses: hasExpectedCropOf some Barley HighWaterUse Type {HighWaterUse , LowWaterUse , MediumWaterUse}	MaizeSorghumRisk Type hasWeedRiskOf some RiskRatingScale CanolaSoybeanRisk Type hasDiseaseRiskOf some RiskRatingScale EquivalentProperties: hasGrowthPropertyOf White_clover_NH Type hasSpecificationOf some FixNitrogen BuckwheatFieldpeaRisk Type hasEconomicRiskOf some RiskRatingScale Berseem_clover_NH Type hasSpecificationOf some RecycleNutrients FieldpeaBarleyRisk Type hasInsectRiskOf some RiskRatingScale Triticale_NH Type hasSpecificationOf some NurseCrop Triticale_NH Type hasSpecificationOf some CoverCropTerminationMethod Teff_NH Type hasWaterUseOf value MediumWaterUse Chickling_vetch_NH Type Vetch hasGrazingPotentialRatingOf SubPropertyOf: hasSpecificationRatingOf Turnip_NH Type hasSpecificationOf some CompanionCrop Pearl_Millet_NH hasRoleRatingOf BelowAverage FieldpeaCanolaRisk Type hasEconomicRiskOf some RiskRatingScale EquivalentClasses: hasEarlyFallRatingOf some SpecificationRatingScale Winter_Rye_NH Type hasSpecificationOf some ShadeTolerant Canola_NH Type hasSpecificationOf some BroadcastInterseed White_clover_NH hasBenefitRatingOf Average Arugula_NH Type hasSpecificationOf some RapidGrowth Grass SubClassOf Grass Arugula_NH Type isAKindOf some CropType Barley_NH Type hasSpecificationOf some TillTermination EquivalentClasses: hasSpecificationOf some LivingMulch EquivalentClasses: CoverCropRole Canola_NH Type hasSpecificationOf some CrimpTermination Sweetclover_NH hasSeedingDepth "0.5"^^xsd:double WheatCanolaRisk Type hasCropResidueOf some Crop Barley_NH Type Crop CoverCrop and ((hasEarlyFallRatingOf some SpecificationRatingScale) or (hasFallRatingOf some SpecificationRatingScale) or (hasLateFallRatingOf some SpecificationRatingScale) or (hasSpringRatingOf some SpecificationRatingScale)) and (isAKindOf some Grain) SubClassOf isLocatedAt some Location EquivalentClasses: NortheasternMountains Buckwheat_NH Type CoverCrop Teff_NH Type hasSpecificationOf some IncreaseSOM Orchardgrass_NH hasRoleRatingOf AboveAverage Fieldpea_NH hasTerminationRatingOf AboveAverage CroppingSystem SubClassOf owl:Thing Millet SubClassOf CoverCrop Turnip_NH Type hasSpecificationOf some IncreaseSOM EquivalentProperties: hasRoleRatingOf owl:Nothing SubClassOf CoverCropItems DormantSeason SubClassOf isSpecificationOf some CoverCrop Cowpea_NH hasGrowthPropertyOf LowWaterUse EarlySummerSeason SubClassOf isSpecificationOf some CoverCrop EquivalentProperties: hasLateFallRatingOf EquivalentClasses: CompanionCrop

C.5 Sample functionality test results

TEST CASE: SUM of item[hasCropRotationRiskOf]

Individual	Expected	Ontology Output
WheatBarleyRisk	9	9
FieldpeaBarleyRisk	11	11
SoybeanBarleyRisk	11	11
CanolaBarleyRisk	10	10
BuckwheatBuckwheatRisk	1	1
SorghumBuckwheatRisk	4	4
FieldpeaBuckwheatRisk	4	4
CanolaBuckwheatRisk	4	4
WheatBuckwheatRisk	5	5
SorghumCanolaRisk	4	4
FieldpeaCanolaRisk	6	6
WheatCanolaRisk	11	11
BarleyCanolaRisk	11	11
BuckwheatCanolaRisk	3	3
SoybeanCanolaRisk	7	7
CanolaCanolaRisk	5	5
WheatFieldpeaRisk	11	11
BarleyFieldpeaRisk	11	11
BuckwheatFieldpeaRisk	6	6
SorghumFieldpeaRisk	6	6
CanolaFieldpeaRisk	8	8
FieldpeaFieldpeaRisk	6	6
SoybeanFieldpeaRisk	8	8
BarleyWheatRisk	8	8
WheatSorghumRisk	4	4
FieldpeaSorghumRisk	4	4
CanolaSorghumRisk	4	4
SorghumSorghumRisk	0	0
WheatSoybeanRisk	12	12
SoybeanSoybeanRisk	7	7
BarleyBarleyRisk	7	7
CanolaSoybeanRisk	8	8
SoybeanWheatRisk	9	9
WheatWheatRisk	6	6
BarleySoybeanRisk	11	11
BuckwheatWheatRisk	5	5
SorghumWheatRisk	5	5
CanolaWheatRisk	9	9
WheatMaizeRisk	2	2
BuckwheatMaizeRisk	4	4
SorghumMaizeRisk	2	2
FieldpeaMaizeRisk	4	4
CanolaMaizeRisk	5	5
MaizeMaizeRisk	0	0
MaizeWheatRisk	6	6
MaizeBuckwheatRisk	3	3
MaizeSorghumRisk	3	3
MaizeCanolaRisk	6	6

Validity: 100.0

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S. Nisperos, and F. McKenzie, "A Sustainability Assessment Model for Crop Rotation Alternatives", ModSim World Conference 2018, Norfolk VA, USA, April 2018.

S. Nisperos, and F. McKenzie, "A Dynamic and Multi-Criteria Sustainability Assessment Model for Crop Rotation Alternatives. 38th Annual PAASE Meeting and Symposium (APAMS 2018), Tucson AZ, USA, April 2018.

S. Nisperos, S. Kakde, and F. McKenzie, "An Agent-Based Simulation of the Impact of Yogic Breathing Adoption". Proc. Summer Simulation Multi-Conference 2017 (SUMMERSIM 2017), Bellevue WA, USA, July 2017, pp. 37:1-37:8, https://dblp.org/db/conf/scsc/scsc2017.html.

S. Nisperos, S. Kakde, and F. McKenzie, "Simulating the Impact of Sudarshan Kriya Yoga in Hampton Roads", ModSim World Conference 2017, Virginia Beach VA, USA, April 2017.

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