OntoCSA: A Climate-Smart Agriculture Ontology

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ABSTRACT

The modelling of agriculture with ontologies has been of interest to many authors in the past years. However, no research, currently, has focused on building a knowledge-based ontology for the climate smart agriculture (CSA) domain. This study attempts to fill this gap through the development of a climate smart agriculture ontology (OntoCSA). Information was gathered from secondary sources including websites, published research articles and reports, as well as related ontologies to formalize the OntoCSA ontology in description logics (DLs). The OntoCSA ontology was developed in web ontology language (OWL) with Protégé. Furthermore, the OntoCSA ontology was successfully validated with the HermiT reasoner within Protégé. The resulting OntoCSA ontology is a machine-readable model of CSA that can be leveraged in web-based applications for the storage, open and automated access, and sharing of CSA information/data for research and dissemination of best practices.

KEYWORDS

Climate Change, Climate Smart Agriculture, Description Logics, Ontology, OWL, Protégé, Semantic Web, Semantic Web Technologies

INTRODUCTION

Climate change poses serious threats to the environment and will negatively impacts human beings, especially agricultural yields. Many threats such as higher carbon dioxide levels, an increase in atmospheric average temperature, varied rainfall patterns, and others can affect agriculture (Raza et al., 2019). In turn, agriculture affects climate change through greenhouse gas emissions and injudicious agricultural practices by humans (Smith & Gregory, 2013). Climate smart agriculture (CSA) is a set of strategies that was introduced in 2010 to tackle the effect of climate change in agriculture (Amin et al., 2015; FAO, 2017). It is a new way of practicing agriculture through the implementation of various techniques that increase productivity in a sustainable manner to achieve food security, provide sustainable solutions and reduce the contributions of agriculture to climate change (Lipper et al., 2014; Amin et al., 2015).

CSA is a knowledge intensive domain that requires innovative and “science-based solutions” (Torquebiau et al., 2018; Lewis & Rudnic, 2019) from multidisciplinary and collaborative research (Lipper et al., 2014; Andrieu et al., 2019; Ardakani et al., 2019; Torquebiau et al., 2018; Lewis &

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Rudnic, 2019). It is a knowledge intensive field in that, many actors from different disciplines such as scientists, academics, farmers, growers, land managers, agro foresters, livestock keepers, fishers, resource managers, NGOs, and policymakers/stakeholders need to collaborate for its successful development and adoption (Lipper et al., 2014; Torquebiau et al., 2018; Lewis & Rudnic, 2019). In such a context, Information and Communication Technologies (ICTs) can play a vital role for the modeling, automation, access, reuse and sharing of information/data for finding suitable solutions as well as sharing of best practices. One suitable ICTs solution for the CSA domain is the use of Semantic Web technologies including ontology, RDFS (Resource Description Framework Schema) and OWL, to formalize the CSA domain in machine-readable formats that can be integrated into the web for the storage, open and automated access and sharing of CSA information/data. RDFS and OWL are two standard languages for representing ontologies; they provide features that enable the representation of ontologies in a machine-readable format to be automatically queried and reasoned to infer new knowledge over the web (Antonioni et al., 2005; Domingue et al., 2011).

An ontology represents a knowledge domain formally, through its entities, concepts, objects and the relationships between them (Busse et al., 2015). Ontology represents common and shared terminologies of a domain (Nidhi et al., 2021) in both conceptual and machine-readable forms, and, thereby, provides a shared comprehension of the representation of information to the community of peoples as well as enables automated processing of knowledge in the domain. Ontology enables the integration of subsystems of a domain and facilitates their interoperability (Taye, 2010; Roussey et al., 2010; Goldstein et al., 2019; Nidhi et al., 2021)). In fact, the subsystems of a domain that use the same ontology process the same terminologies, which may facilitate their integration and interoperability. Alternatively, if a separate ontology has been developed for each subsystem, the terminologies in the ontologies of subsystems can be matched to integrate the subsystems (Goldstein et al., 2019).

The Semantic Web is the extended version of the web in which contents are represented based on their meaning rather than hyperlinks as in the current internet, for both human and machine understanding (Shadbolt, 2006; Taye, 2010). The meaning of web content on the Semantic Web is represented with ontology in logic-based languages such as RDFS and OWL; this enables the development of intelligent web-based applications that can automatically query and reason the web contents to infer new information on behalf of users (Shadbolt, 2006; Taye, 2010; Goldstein et al., 2019).

Although the semantic modelling of agriculture has attracted researchers in recent years (Ramar & Gurunathan, 2017; Jebaraj & Sathiaselvan, 2017; Goldstein et al., 2019; Drury et al., 2019; Kessler et al., 2021; Roussey et al., 2021; Abayomi-Alli et al., 2021) and has resulted in the development of ontologies for agriculture (Hu et al., 2011; Kim et al., 2013; Jebaraj & Sathiaselvan, 2017; Ngo et al., 2018; Arnaud et al., 2020; Jachimczyk et al., 2021; Nidhi et al., 2021), no research to date has focused on building a knowledge base ontology for the CSA domain. This study attempts to fill this gap through the development of a Climate Smart Agriculture Ontology (OntoCSA). The OntoCSA ontology represents common and shared terminologies of the CSA domain in a machine-readable format for all role players in the field and can be used to integrate and facilitate the interoperability of subsystems of scientists, academics, agro foresters, fishers, livestock keepers and others, for collaborative research and innovations as well as sharing of data and best practices. Furthermore, in this era of big data and machine learning, the OntoCSA ontology can be used to store relevant CSA data that can serve to draw various statistical analyses for research and decision making. Moreover, the OntoCSA ontology can be integrated with existing agricultural ontologies (Hu et al., 2011; Song et al., 2012; Dineshkumar et al., 2014; Ngo et al., 2018) to build comprehensive ontologies for the agriculture domain that include today's realities of climate change in agriculture.

Information was gathered from secondary sources including websites ("Climate Smart Agriculture", n.d.; Papuso & Faraby, 2013; FAO, 2017), published research articles and reports (Smith & Gregory, 2012; Lipper et al., 2014; Amin et al., 2015; FISH, 2016; FAO, 2018a; Raza et al., 2019) as well as related ontologies (Hu et al., 2011; Kim et al., 2013; Ngo et al., 2018), to

formalize the OntoCSA ontology in DLs (Description Logics). DLs is a group of languages that provide features for representing ontology's elements including concepts/classes, properties/roles, instances/individuals and their combination with operators such as union, intersection, negation, etc., as well as restrictions/constraints on these elements (Krotzsch et al., 2012). The modelling of an ontology in DLs facilitates its implementation in OWL because the syntax of the OWL language is based on DLs. The DLs representation of the OntoCSA ontology was implemented in OWL with Protégé (Musen, 2015). Protégé is a software that one can download free of charge from the internet to develop ontologies. Moreover, the resulting OntoCSA ontology was successfully validated for query, reasoning and consistency with the HermiT reasoner within Protégé.

The remaining of the paper has the following structure. In Section 2, the related studies are discussed. The methodology is presented and applied in Section 3 to formalize the OntoCSA ontology in DLs. Section 4 explains the implementation and results achieved. A discussion follows in Section 5 and a conclusion ends the paper.

LITERATURE REVIEW

The adoption of semantic technologies in agriculture has been an active research area in recent years. This is witnessed in recent reviews of the use of semantic technologies in agriculture (Jebaraj & Sathiaselalan, 2017; Drury et al., 2019) and a recent review and evaluation of existing agricultural ontologies (Goldstein et al., 2019). Many studies have specifically reported on the use of ontologies in agriculture (Hu et al., 2011; Kim et al., 2013; Dineshkumar et al., 2014; Harika & Bhargav, 2015; Sivamani et al., 2016; Jebaraj & Sathiaselalan, 2017; Ngo et al., 2018; Goldstein et al., 2019; Nidhi et al., 2021; Jachimczyk et al., 2021) and climate change (Diop & Lo, 2013; Pileggi & Lamia, 2020) domains.

Kim et al. (2013), Harika and Bhargav (2015) and Sivamani et al. (2016) developed context aware ontologies for seamless services access in vertical farming. The proposed ontologies model the vertical farm environment and the factors that influence crop growth in such an environment. Although vertical farming may be considered as a CSA technique, the proposed ontologies did not address the topic of climate change in agriculture.

An ontology named AgOnt was proposed by Hu et al. (2011), to address the interoperability problem between heterogeneous agriculture data sources. The ArgOnt ontology represents the lifecycle of agricultural products with five top concepts including product, location, time, phase and condition. These main concepts are further extended with sub-concepts to better represent the agriculture domain. For instance, the phase concept has sub-concepts such as cultivation, harvest, storage, transportation, processing and sales. Similar research was undertaken by Ngo et al. (2018) in which another agriculture ontology, namely, AgriOnt was proposed for an integrated framework for smart agriculture systems. The AgriOnt ontology has four modules including geographical, Internet of Things (IoT)-based, business-based and agricultural-based. The agricultural-based module is an extension of the AgOnt including the main concepts such as farm, crop, product, phase, fertilizer and condition. Other modules of the AgriOnt are extended with more sub classes to represent complete IoT-based agriculture systems. The concepts of AgOnt (Hu et al., 2011) and AgriOnt (Ngo et al., 2018) ontologies provide an extensive overview of agricultural farming; however, their design did not include any concepts on climate change in agriculture.

Another study by Dineshkumar et al. (2014) used a modular approach to model the agriculture domain with ontologies. The agriculture domain was divided into 4 subdomains including crop, crop diseases, soil and climate. Thereafter, an ontology was designed to model each subdomain. The ontologies of the subdomains were then combined to build a complete ontology of the agriculture domain. Although the study developed an ontology module to represent climate in agriculture, it did not specifically address climate change in agriculture. However, the proposed agriculture ontology can be extended with the OntoCSA ontology proposed in this study through its climate module, to

obtain a comprehensive agriculture ontology. Song et al. (2012) used a similar approach to model the agriculture domain. The authors used three modules to represent the information on crop, the conditions that affect crop and the production cycle of crop at various phases.

Other studies on ontologies and taxonomies for agricultures are reported by FAO (2021), Beck et al. (2010), Li et al. (2014), Liao et al. (2015), Tomic et al. (2015), Wang et al. (2015) and Nidhi et al. (2021). The FAO developed the AGROVOC thesaurus (FAO, 2021) which includes concepts on food and agriculture. An ontology that models knowledge on citrus production was developed by Wang et al. (2015); this ontology specifically models fertilization and irrigation in citrus production. Another citrus ontology was developed by Liao et al. (2015) and used an integrated ontology-based information system for agriculture. Beck et al. (2010) developed an ontology-based simulation system and applied it to model concepts related to citrus and sugarcane and included soil, water and nutrients. Domain and tasks ontologies were used to model crop cultivation standards by Li et al. (2013); the domain ontology models the physical infrastructure, whereas, the task ontology represents the operations for crop cultivation. Tomic et al. (2015) used ontology to model dairy farming knowledge with the aim of enabling the integration of various heterogeneous data sources for intelligent information management. A recent study by Nidhi et al. (2021) proposed an ontology model which provides a generic representation of fertilizers.

Climate change has also been modelled with ontologies by Diop & Lo (2013) and Pileggi & Lamia (2020). Pileggi and Lamia (2020) developed the Climate Change Time-Line (CCTL) ontology to model the scientific, social and political elements associated with climate change. Although well documented, the CCTL ontology excludes the specific topic of climate change in agriculture. An ontology design pattern for climate change, namely, OntoCLUVA, was proposed by Diop & Lo (2013). OntoCLUVA is a generic ontology for climate change that can be extended to represent various climate change subdomains. However, no specific consideration of climate change in agriculture was included in the OntoCLUVA ontology.

It appears that, although efforts have been made to develop ontologies for both the agriculture and climate change domains, no study has attempted to model the CSA domain with ontology to date. To the authors knowledge, this is the first report to develop an ontology of CSA. The OntoCSA ontology proposed, in this study, can be integrated with existing agriculture ontologies (Hu et al., 2011; Dineshkumar et al., 2014; Ngo et al., 2018), to build current ontologies for the agriculture domain, that include today's realities of climate change in agriculture. The methodology used in this study is presented and applied in the next section.

METHODOLOGY

The ontology development methodology 101 (OD101) by Noy and McGuinness (2001) is used to build the OntoCSA ontology. The OD101 methodology was adapted by Ye-lu et al. (2012) and prescribed as the “universal” methodology for building agricultural ontologies. The OD101 methodology prescribes a number of steps for a quick formalization of a domain in a logic-based syntax. The OD101 methodology has three phases. The first phase comprises the first three steps of the methodology, namely, definition of the scope of ontology, reusing existing ontologies and creating a glossary of terms; this results in the construction of the vocabulary of the target ontology. The following three steps of the OD101 methodology prescribes the definition of classes, properties and instances of the ontology from the vocabulary obtained in the previous steps and constitute the second phase. In the third and last phase of the OD101 methodology, modeling of the target ontology in a logic based syntax is prescribed. The abovementioned three phases of the methodology are implemented next.

Building the Vocabulary of the CSA Domain

The vocabulary of the CSA domain was constructed by reading related literature on CSA from websites (“Climate-Smart Agriculture”, n.d.; Papuso & Faraby, 2013; FAO, 2017), published research articles

and reports (Smith & Gregory, 2012; Lipper et al., 2014; Amin et al., 2015; FISH, 2016; FAO, 2018a; Raza et al., 2019) and analyzing existing related agricultural ontologies (Hu et al., 2011; Kim et al., 2013; Dineshkumar et al., 2014; Harika & Bhargav, 2015; Sivamani et al., 2016; Ngo et al., 2018). Furthermore, lists of competency questions (CQs) and role players involved in CSA were drawn to delimit the scope of the target OntoCSA ontology. Table 1 shows the list of 16 competency questions that were formulated.

Table 1. List of Competency Questions

	Competency Questions
1	What are the CSA techniques?
2	Who are the role players in the execution of CSA techniques?
3	Who are the developers of CSA techniques?
4	Who are the users of CSA?
5	What resources does CSA require?
6	What are the current CSA violations?
7	What are the current best practices for CSA?
8	What are the indicators for successful CSA practices?
9	What are the indicators for short term monitoring and evaluation of CSA responses to climate change?
10	What are the risk factors associated with CSA?
11	What are the difficulties in executing CSA?
12	What are the current legislations governing CSA?
13	To what extend is government involved in CSA?
14	What are the funding option available for CSA?
15	To what extent is CSA sustainable?
16	Who are the beneficiaries of CSA?

The list of roles players in the CSA domain was also established, including CSA users, CSA developers, CSA financiers and CSA endorsers. CSA users are people who directly use CSA techniques and include farmers, individuals with home gardens, nursery owners, etc. (Amin et al., 2015; FAO, 2018a; Andrieu et al., 2019). To create CSA solutions, innovative research and testing needs to be done. CSA developers, consisting of research scientists, specialists and academics are responsible for this role (Lipper et al., 2014; Lewis & Rudnic, 2019). To realize CSA, financing is an essential factor. NGOs and governments are common financiers for agriculture (Lipper et al., 2014; Steenwerth et al., 2014). CSA endorsers are individuals/organizations including the United Nations, lobbyists and activists (Steenwerth et al., 2014). Other less important actors are the people involved in the selling of CSA produce and those who consume or use the produces (Lewis & Rudnic, 2019). Instances or individuals of classes were also gathered. For example, the instances of the *Livestock Management* class include *feed quality*, *change rainfall patterns*, *overgrazing*, *appropriate housing and spacing*, *improved feeding strategies*, *rotational grazing* and *manure treatment*. A total of 88 instances were collected for the CSA domain. The vocabulary of the domain was completed with the identification of properties or relations between the classes and instances of CSA domain. The information collected enabled the construction of the vocabulary of the OntoCSA ontology; this vocabulary encompasses the classes, individuals/instances and property/reasons. The concepts/classes of the CSA domain

represented the main terminologies of the CSA domain such as soil, crop, livestock, water, forestry, agroforestry, energy, fishery, aquaculture, food seller, and so forth.

Based on the vocabulary of the CSA domain, 169 statements in natural language were further formulated to comprehensively describe the CSA domain. These statements represent the various types of relationships between classes and instances in the OntoCSA ontology, including taxonomy or inheritance relationships, binary relationships between two classes or individuals of the ontology and class assertion or unary relationships between classes and instances of the ontology. Specifically, class assertion or unary relationships represent the instances or individuals of classes in the OntoCSA ontology. For example, the following statement “*Produce is farmed by Farmer*”, of the CSA domain represents the binary relationship “*is farmed by*” between the classes *Produce* and *Farmer* in the OntoCSA ontology. Other examples of statements of the CSA domain including “*A farmer is a CSA user*” and “*A physical barrier is a CSA barrier*”, represent taxonomies or inheritance relationships between the pair of classes *Farmer* and *CSA User*, and *Physical Barrier* and *CSA Barrier*, respectively. Further examples of statements that describe the CSA domain and represent class assertions encompass: “*Changed rainfall patterns is a Climate Change signal*”, “*Deforestation is a Climate Change Contributor*” and “*Contour planting is a CSA technique*”; these statements represent that “*Changed rainfall patterns*” is an instance or individual of the *Climate Change Signal* class in the OntoCSA ontology; similarly, *Deforestation* and *Contour planting* are instances of *Climate Change Contributor* and *CSA technique* classes in the OntoCSA ontology, respectively. The full list of the 169 statements of the CSA domain that have been modelled in the OntoCSA ontology is available at (“CSA natural language statements”, 2021). These statements of the CSA domain are represented in logic-based syntaxes in the next subsection.

Logic-Based Representation of the OntoCSA Ontology

The above statements of the CSA domain were further represented in logic-based syntaxes including First-order-logic (FOL) and DLs to form the axioms of the OntoCSA ontology. FOL is an extension of the propositional logic; it enables the representation of things in the world with objects, relations/predicates and functions (Keet, 2020). The FOL syntax expresses knowledge in the natural language; therefore, it is an intermediate step from the natural language statements to DLs concepts. Table 2 presents the FOL formulas for some statements of the CSA domain.

The reference numbers in the left column of Table 2 indicates the corresponding indexes of the statements in the original list of these statements. In summary, the FOL formulas in Table 2 represent:

- The people who farm, sell, buy and consume the produce of CSA (indexes 1-6), the physical and non-physical barriers to CSA (indexes 48 and 49),
- The management types of CSA (indexes 63-70) including soil, crop, livestock, water, agro forestry, fisheries and aquaculture, energy and integrated food energy systems,
- Some climate change signals (indexes 73-89) such as soil erosion, soil leaching, increased temperature, extreme weather, rising sea levels, weeds, pests, diseases, dry spell, increased salinity, change in ocean acidity, water scarcity, flooded systems, crop water stress, feed quality, change in rainfall pattern, change in ocean temperature, and loss of biodiversity,
- The contributors to climate change (indexes 90-95) including overgrazing, rising emissions, deforestation, fossil fuels, unsustainable harvested wood, and land use, and
- Some CSA techniques (indexes 96-99 and 101-103) such as minimum tillage, contour planting, plant mounds, mulching, heat flood and saline tolerant varieties, shade house and composting.

The statements of the CSA domain were further represented in DLs in preparation for their implementation in Protégé. Table 3 presents the corresponding DLs concepts of FOL formulas in Table 2. Various types of axioms or statements of the OntoCSA ontology are represented in DLs in Table 3 including (1) properties or roles; they are binary predicates such as *isFarmedBy*, *isSold*,

Table 2. Part of FOL Representation of Axioms of the OntoCSA Ontology

	FOL Formulas
1	$\exists x \exists y (\text{Produce}(x) \hat{\cup} \text{Farmer}(y) \hat{\cup} \text{isFarmedBy}(x, y))$
2	$\exists x \exists y (\text{Produce}(x) \hat{\cup} \text{NurseryOwner}(y) \hat{\cup} \text{isFarmedBy}(x, y))$
3	$\exists x \exists y (\text{Produce}(x) \hat{\cup} \text{HomeGardenOwner}(y) \hat{\cup} \text{isFarmedBy}(x, y))$
4	$\forall x (\text{Produce}(x) @ \exists y (\text{FoodSeller}(y) \hat{\cup} \text{isSoldBy}(x, y)))$
5	$\forall x (\text{Produce}(x) @ \exists y (\text{Consumer}(y) \hat{\cup} \text{isBoughtBy}(x, y)))$
6	$\forall x (\text{Produce}(x) @ \exists y (\text{Consumer}(y) \hat{\cup} \text{isConsumedBy}(x, y)))$
7	$\forall x (\text{Farmer}(x) @ \text{CSAUser}(x))$
48	$\forall x (\text{PhysicalBarrier}(x) @ \text{CSABarrier}(x))$
49	$\forall x (\text{NonPhysicalBarrier}(x) @ \text{CSABarrier}(x))$
63	$\forall x (\text{SoilManagement}(x) @ \text{ManagementType}(x))$
64	$\forall x (\text{CropManagement}(x) @ \text{ManagementType}(x))$
65	$\forall x (\text{LiveStockManagement}(x) @ \text{ManagementType}(x))$
66	$\forall x (\text{WaterManagement}(x) @ \text{ManagementType}(x))$
67	$\forall x (\text{AgroForestryManagement}(x) @ \text{ManagementType}(x))$
68	$\forall x (\text{FisheriesAndAquaCultureManagement}(x) @ \text{ManagementType}(x))$
69	$\forall x (\text{EnergyManagement}(x) @ \text{ManagementType}(x))$
70	$\forall x (\text{IntegratedFoodEnergySystem}(x) @ \text{ManagementType}(x))$
73	$\forall x (\text{SoilErosion}(x) @ \text{ClimateChangeSignal}(x))$
74	$\forall x (\text{SoilLeaching}(x) @ \text{ClimateChangeSignal}(x))$
75	$\forall x (\text{WaterScarcity}(x) @ \text{ClimateChangeSignal}(x))$
76	$\forall x (\text{FloodedSystem}(x) @ \text{ClimateChangeSignal}(x))$
77	$\forall x (\text{CropWaterStress}(x) @ \text{ClimateChangeSignal}(x))$
78	$\forall x (\text{IncreasingSalinity}(x) @ \text{ClimateChangeSignal}(x))$
79	$\forall x (\text{ChangeInOceanAcidity}(x) @ \text{ClimateChangeSignal}(x))$
80	$\forall x (\text{ChangeOceanTemperature}(x) @ \text{ClimateChangeSignal}(x))$
81	$\forall x (\text{TemperatureIncrease}(x) @ \text{ClimateChangeSignal}(x))$
82	$\forall x (\text{ExtremeWeather}(x) @ \text{ClimateChangeSignal}(x))$
83	$\forall x (\text{RisingSeaLevel}(x) @ \text{ClimateChangeSignal}(x))$
84	$\forall x (\text{WeedsPestDisease}(x) @ \text{ClimateChangeSignal}(x))$
85	$\forall x (\text{DrySpell}(x) @ \text{ClimateChangeSignal}(x))$
86	$\forall x (\text{ChangeRainFallPattern}(x) @ \text{ClimateChangeSignal}(x))$
87	$\forall x (\text{FeedQuality}(x) @ \text{ClimateChangeSignal}(x))$
88	$\forall x (\text{LostOfBiodiversity}(x) @ \text{ClimateChangeSignal}(x))$
89	$\forall x (\text{InorganicFertilizer}(x) @ \text{ClimateChangeSignal}(x))$
90	$\forall x (\text{Overgrazing}(x) @ \text{ClimateChangeContributor}(x))$
91	$\forall x (\text{RisingEmission}(x) @ \text{ClimateChangeContributor}(x))$
92	$\forall x (\text{Deforestation}(x) @ \text{ClimateChangeContributor}(x))$
93	$\forall x (\text{FossilFuels}(x) @ \text{ClimateChangeContributor}(x))$
94	$\forall x (\text{UnsustainablyHarvestedWood}(x) @ \text{ClimateChangeContributor}(x))$
95	$\forall x (\text{LandUse}(x) @ \text{ClimateChangeContributor}(x))$

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Table 2. Continued

	FOL Formulas
96	$\forall x(\text{MinimumTillage}(x) \text{ @ } \text{CSATechnique}(x))$
97	$\forall x(\text{ContourPlanting}(x) \text{ @ } \text{CSATechnique}(x))$
98	$\forall x(\text{PlantMounds}(x) \text{ @ } \text{CSATechnique}(x))$
99	$\forall x(\text{Mulching}(x) \text{ @ } \text{CSATechnique}(x))$
101	$\forall x(\text{HeatFoodAndSalineTolerantVarieties}(x) \text{ @ } \text{CSATechnique}(x))$
102	$\forall x(\text{ShadeHouse}(x) \text{ @ } \text{CSATechnique}(x))$
103	$\forall x(\text{Composting}(x) \text{ @ } \text{CSATechnique}(x))$

isBoughtBy and *isConsumedBy* (indexes 1-6); they represent the relationships between concepts in the ontology, (2) taxonomies or class inclusions; they are represented with the inclusion symbols and are the inheritance relations amongst the concepts of the ontology (indexes 48-49 and 63-70) and (3) class assertions or unary predicates that define the instances or individuals of concepts in the ontology (indexes 73-103). The implementation of the CSA ontology from its DLs representation is reported in the next section.

IMPLEMENTATION

This section presents the implementation of the OntCSA ontology in terms of the computer and software environments that were used in the experiments, the presentation and discussion of results and the evaluation of the OntoCSA ontology.

Computer and Software Environments

The OntoCSA ontology was developed in Protégé version 5.5 on a computer with the following characteristics: Lenovo V310-151KB, Windows 10 Pro operating System, x64-based processor with 2.50GHz CPU and 4,00GB RAM.

RESULTS AND DISCUSSIONS

The screenshot in Figure 1 depicts the implementation of the OntoCSA ontology in Protégé. The top left of Figure 1 shows the taxonomy of classes in the OntoCSA ontology. At the bottom left of Figure 1, some climate smart agriculture techniques which are the instances of the *CSA technique* class in the ontology are displayed. On the top and bottom right of Figure 1, “*crop rotation*” is represented as an individual/instance of the *Crop management* and *CSA technique* classes in the ontology.

Furthermore, the graphical representation of the taxonomy of classes in the OntoCSA ontology is shown in Figure 2. The OWL Viz which is a Protégé plug-in was used to generate the picture in Figure 2 that shows the super and subclasses in the OntoCSA ontology.

Other important constituents of the OntoCSA ontology named properties are displayed on the left panel of Figure 3. They are the relations/roles in the ontology. In particular, there are domains and ranges for binary relations or predicates. The domains are the concepts defined by the properties, whereas, ranges are the instances or occurrences of the properties.

For instance, the top and bottom right of Figure 3 shows the domains and range of the property *contributeTo*, highlighted on the left panel. In other words, the property *contributeTo* defines the classes Climate Change Contributor (*CC Contributor*) and Climate Change Signal (*CC Signal*) which are its domains, and it has the class Climate Smart Agriculture Violation (*CSA Violation*) as range or instance.

Table 3. Part of DLs Representation of Axioms of the OntoCSA Ontology

	OWL Axioms
1	$\exists \text{Produce} \sqcap \exists \text{isFarmedBy.Farmer}$
2	$\exists \text{Produce} \sqcap \exists \text{isFarmedBy.NurseryOwner}$
3	$\exists \text{Produce} \sqcap \exists \text{isFarmedBy.HomeGardenOwner}$
4	$\text{Produce} \sqsubseteq \exists \text{isSoldBy.FoodSeller}$
5	$\text{Produce} \sqsubseteq \exists \text{isBoughtBy.Consumer}$
6	$\text{Produce} \sqsubseteq \exists \text{isConsumedBy.Consumer}$
7	$\text{Farmer} \sqsubseteq \text{CSAUser}$
48	$\text{PhysicalBarrier} \sqsubseteq \text{CSABarrier}$
49	$\text{NonPhysicalBarrier} \sqsubseteq \text{CSABarrier}$
63	$\text{SoilManagement} \sqsubseteq \text{ManagementType}$
64	$\text{CropManagement} \sqsubseteq \text{ManagementType}$
65	$\text{LiveStockManagement} \sqsubseteq \text{ManagementType}$
66	$\text{WaterManagement} \sqsubseteq \text{ManagementType}$
67	$\text{AgroForestryManagement} \sqsubseteq \text{ManagementType}$
68	$\text{FisheriesAndAquaCultureManagement} \sqsubseteq \text{ManagementType}$
69	$\text{EnergyManagement} \sqsubseteq \text{ManagementType}$
70	$\text{IntegratedFoodEnergySystem} \sqsubseteq \text{ManagementType}$
73	$\text{ClimateChangeSignal}(\text{SoilErosion})$
74	$\text{ClimateChangeSignal}(\text{SoilLeaching})$
75	$\text{ClimateChangeSignal}(\text{WaterScarcity})$
76	$\text{ClimateChangeSignal}(\text{FloodedSystem})$
77	$\text{ClimateChangeSignal}(\text{CropWaterStress})$
78	$\text{ClimateChangeSignal}(\text{IncreasingSalinity})$
79	$\text{ClimateChangeSignal}(\text{ChangeInOceanAcidity})$
80	$\text{ClimateChangeSignal}(\text{ChangeOceanTemperature})$
81	$\text{ClimateChangeSignal}(\text{TemperatureIncrease})$
82	$\text{ClimateChangeSignal}(\text{ExtremeWeather})$

continued on next page

Table 3. Continued

	OWL Axioms
83	ClimateChangeSignal(RisingSeaLevel)
84	ClimateChangeSignal(WeedsPestDisease)
85	ClimateChangeSignal(DrySpell)
86	ClimateChangeSignal(ChangeRainFallPattern)
87	ClimateChangeSignal(FeedQuality)
88	ClimateChangeSignal(LostOfBiodiversity)
89	ClimateChangeSignal(InorganicFertilizer)
90	ClimateChangeContributor(Overgrazing)
91	ClimateChangeContributor(RisingEmission)
92	ClimateChangeContributor(Deforestation)
93	ClimateChangeContributor(FossilFuels)
94	ClimateChangeContributor(UnsustainablyHarvestedWood)
95	ClimateChangeContributor(LandUse)
96	CSATechnique(MinimumTillage)
97	CSATechnique(ContourPlanting)
98	CSATechnique(PlantMounds)
99	CSATechnique(Mulching)
101	CSATechnique(HeatFoodAndSalineTolerantVarieties)
102	CSATechnique(ShadeHouse)
103	CSATechnique(Composting)

Figure 1. Protégé Implementation of OntoCSA Ontology

Figure 2. Taxonomy of Class Hierarchy in OntoCSA Ontology

Figure 3. OntoCSA Properties in Protégé

Figure 4. Outcomes of (a) Inference of Individuals by Type from the OntoCSA Ontology and (b) Successful Consistency Check of OntoCSA Ontology, with the Hermit Reasoner in Protégé

Figure 5. Part of OWL Code of OntoCSA Ontology

```
<!-- http://webprotege.stanford.edu/isBoughtBy -->

<owl:ObjectProperty rdf:about="http://webprotege.stanford.edu/isBoughtBy">
  <rdfs:subPropertyOf rdf:resource="http://www.w3.org/2002/07/owl#topObjectProperty"/>
  <rdfs:domain rdf:resource="http://webprotege.stanford.edu/Produce"/>
  <rdfs:range rdf:resource="http://webprotege.stanford.edu/Food_Consumer"/>
  <rdfs:label xml:lang="en">isBoughtBy</rdfs:label>
</owl:ObjectProperty>

<!-- http://webprotege.stanford.edu/isConsumedBy -->

<owl:ObjectProperty rdf:about="http://webprotege.stanford.edu/isConsumedBy">
  <rdfs:subPropertyOf rdf:resource="http://www.w3.org/2002/07/owl#topObjectProperty"/>
  <rdfs:domain rdf:resource="http://webprotege.stanford.edu/Produce"/>
  <rdfs:range rdf:resource="http://webprotege.stanford.edu/Food_Consumer"/>
  <rdfs:label xml:lang="en">isConsumedBy</rdfs:label>
</owl:ObjectProperty>

<!-- http://webprotege.stanford.edu/isDevelopedBy -->

<owl:ObjectProperty rdf:about="http://webprotege.stanford.edu/isDevelopedBy">
  <rdfs:subPropertyOf rdf:resource="http://www.w3.org/2002/07/owl#topObjectProperty"/>
  <rdfs:domain rdf:resource="http://webprotege.stanford.edu/CSA_Technique"/>
  <rdfs:domain rdf:resource="http://webprotege.stanford.edu/Climate_Smart_Agriculture"/>
  <rdfs:range rdf:resource="http://webprotege.stanford.edu/CSA_Developer"/>
  <rdfs:label xml:lang="en">isDevelopedBy</rdfs:label>
</owl:ObjectProperty>
```

Figure 6. Sample Results of SPARQL query execution on OntoCSA Ontology in Protégé

SPARQL query	
<pre> PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> PREFIX owl: <http://www.w3.org/2002/07/owl#> PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#> PREFIX xsd: <http://www.w3.org/2001/XMLSchema#> SELECT ?subject ?object WHERE { ?subject rdfs:subClassOf ?object } </pre>	
subject	
Agroforestry & Forestry Management	Management Type
CSA Developer	Climate Smart Agriculture
Physical Barrier	CSA Barrier
Food Seller	Climate Smart Agriculture
Produce	Climate Smart Agriculture
CSA Barrier	Climate Smart Agriculture
CSA User	Climate Smart Agriculture
CC Contributor	CSA Violation
Water Management	Management Type
CSA Technique	Climate Smart Agriculture
Crop Management	Management Type
Non-Physical Barrier	CSA Barrier
Integrated Food Energy System	Management Type
CSA Violation	Climate Smart Agriculture
Financier	Climate Smart Agriculture
Soil Management	Management Type
Management Type	Climate Smart Agriculture
Food Consumer	Climate Smart Agriculture
CC Signal	CSA Violation
Energy Management	Management Type

Evaluation of OntoCSA Ontology

The HermiT reasoner was used to evaluate the OntoCSA ontology within Protégé. The reasoner enabled to ascertain the suitability of the OntoCSA ontology for automated reasoning tasks such as query and inference and classification. The results of using the HermiT reasoner to infer individuals by type is shown in Figure 4 (a), and constituted the class *CC Signal* and its 16 inferred instances in the OntoCSA ontology.

The reasoner was also invoked to perform a consistency check between the classes of the OntoCSA ontology. Figure 4 (b) depicts the result of the consistency check of the OntoCSA ontology, which shows the same OntoCSA class hierarchy in Figure 1, without any class highlighted in red. In fact, any inconsistency in the OntoCSA ontology would have resulted in the implicated classes being highlighted in red in Figure 4(b). In other words, Figure 4 (b) shows that there are no inconsistencies between the classes of the OntoCSA ontology. Therefore, the OntoCSA ontology is consistent and suitable for reasoning tasks.

A part of the code of the OntoCSA ontology in OWL language is given in Figure 5. The sample code represents the *isBoughtBy*, *isConsumedBy* and *isDevelopedBy* properties of the OntoCSA ontology along with their domains and ranges. For instance, the bottom part of the OWL code in Figure 5 represents the domains of the *isDevelopedBy* property which are the *CSA Technique* and *Climate Smart Agriculture* classes and its range the *CSA Developer* class. Finally, SPARQL queries were run on the OntoCSA ontology. Figure 6 shows an example of a SPARQL query which maps subclasses (bottom left) to their respective super classes in the ontology (bottom right). The implication of the adoption of OntoCSA in agriculture is presented in the next section.

Implication of OntoCSA on Agriculture

The OntoCSA ontology represents common and shared terminologies of the CSA domain in a machine-readable format for all role players in the field and can be used in Internet of Things (IoT) based web applications (Jachimczyk et al., 2021) to integrate and facilitate the interoperability of subsystems of scientists, academics, agro foresters, fishers, livestock keepers and others, for collaborative research and innovations as well as sharing of data and best practices. This would lead to the successful and worldwide adoption of CSA practices, which would (1) reduce the amount of resources needed by farmers such as money, fuel and water, (2) increase crop yield or livestock (CCAFS, 2014) and (3) provide food security to mainly poor and vulnerable communities in many parts of the world.

Furthermore, in this era of big data and machine learning, the OntoCSA ontology can be used to store relevant CSA data that can serve to draw various statistical analyses for agricultural research and decision making. Moreover, some terminologies of existing agriculture ontologies (Hu et al., 2011; Song et al., 2012; Dineshkumar et al., 2014; Ngo et al., 2018) such as crop, farm, livestock, agroforestry, water, soil, fishery, aquaculture, energy, etc. have been reused in the OntoCSA ontology. These concepts may be utilized to match and integrate the OntoCSA ontology with exiting agriculture ontologies and to build more comprehensive knowledge base ontologies for the agriculture domain that include the current realities of climate change in agriculture. However, despite the above benefits of the OntoCSA ontology in agriculture there are some challenges to the widespread adoption of CSA practices such as the (1) high cost and availability of agricultural inputs, (2) higher labor needs, (3) probability of failure of CSA practices and (4) shortage of skilled farmers to implement the CSA practices (CCAFS, 2014).

Figure 7. Some Logical Axioms of OntoCSA Ontology

■ usedToPlant Domain 'CSA Technique'
■ usedToPlant Range Crop
■ plantedAt Domain Crop
■ plantedAt Range Farm
■ madeFrom Domain Produce
■ madeFrom Range Crop
■ madeIn Domain Produce
■ madeIn Range Location
■ hasLocation Domain Farm
■ hasLocation Range Location
■ implements Domain Farm
■ implements Range 'CSA Technique'
■ ownedBy Domain Farm
■ ownedBy Range 'CSA User'
■ affiliatedWith Domain 'CSA Developer'
■ affiliatedWith Range Organization
■ isDevelpedBy Domain 'CSA Technique'
■ isDevelpedBy Range 'CSA Developer'

Case Studies of CSA Projects in OntoCSA Ontology

The OntoCSA ontology provides a generic model of the CSA domain and does not address any specific case of CSA practice. Therefore, the OntoCSA ontology can be populated in web-based applications with specific case studies of CSA farming and research initiatives, through concepts such as farm, crop, location, organization, produce, CSA user, CSA developer, CSA technique, and so forth, illustrated in some axioms of the ontology in Figure 7. The axioms in Figure 7 represent from top to bottom that, “a CSA technique is used to plant a crop”, “a crop is planted at a farm”, “a produce is made from a farm”, “a produce is made in a location”, “a farm has a location”, “a farm implements a CSA technique”, “a farm is owned by a CSA user”, “a CSA developer is affiliated with an organization” and “a CSA technique is developed by a CSA developer”. These axioms are

important facts in the OntoCSA ontology that can be used to record relevant information on case studies and research initiatives in CSA, for the purpose of collaboration and sharing of best practices in the CSA domain. To illustrate this, the OntoCSA ontology was populated with five CSA projects (FAO, 2018b). These projects are listed at the bottom of the left panel of Figure 8 and include (1) the floating gardens projects in Bangladesh, (2) the Great Green Wall initiative for the Sahara and the Sahel in Burkina Faso and Niger, (3) the integrated climate smart production system project that spans across four Latin American countries including El Salvador, Guatemala, Honduras and Nicaragua, (4) the Kagera transboundary agro-ecosystem management project in Burundi and (5) the sloping agricultural land technology in coconut farming communities projects in Philippines.

For each of the five case studies of CSA projects in Figure 8, the description/title, CSA developer, CSA user, CSA techniques implemented, CSA financier, etc., were populated in the OntoCSA ontology. In particular, it is highlighted on the bottom left panel of Figure 8 the Kagera transboundary agro-ecosystem management project in Burundi. The top and bottom parts of the right panel of Figure 8 show the axioms of the OntoCSA ontology that represent (1) the CSA techniques implemented in this project including improve seeds, rainwater harvesting, and pest control management, (2) the CSA developer of the project which is the FAO and (3) the financier of the project which is an organization called Global Environment Facility. Interested readers may find more information on these CSA projects (FAO, 2018b).

Figure 8. Case Studies of CSA Projects in the OntoCSA Ontology

LIMITATIONS OF THE STUDY

The methodology employed to develop the OntoCSA ontology relied on secondary sources of information or data from the internet. Some factors such as the large size of the internet, access restriction on some sources and unreported ongoing or completed research on CSA projects around the world, may have prevented access to some relevant information on climate smart agriculture; this may have resulted in the omission of some minor relevant CSA terminologies from the OntoCSA ontology. Such omissions could be used to update the OntoCSA ontology as soon as they are available. Despite this shortcoming, the authors believe that the scope of the OntoCSA ontology, the sources consulted, the existing agricultural ontologies analyzed and reused and the amount of 169 natural

language statements (“CSA natural language statements”, 2021) collected to describe the CSA domain in this study, make the OntoCSA ontology the first comprehensive semantic modelling of the CSA domain to date.

CONCLUSION

This study developed an ontology for the CSA domain, namely, OntoCSA ontology. The OntoCSA ontology represents common and sharable terminologies of the CSA domain in a machine-readable format for all role players in the field. The OntoCSA ontology can be used to integrate and facilitate the interoperability of subsystems of scientists, academics, agro foresters, fishers, livestock keepers and many more, for collaborative research and innovations as well as sharing of data and best practices. Furthermore, in this era of IoT, big data and machine learning, the OntoCSA ontology can be used to develop ubiquitous systems to store relevant CSA data that can serve to draw various statistical analyses for research and decision making. Moreover, the OntCSA ontology can be integrated with existing agriculture ontologies to develop more comprehensive and up to date ontologies of the agriculture domain, that include todays realities of climate change in agriculture.

The future direction of this research would be to populate the OntoCSA ontology with case studies of CSA practices from around the world and apply machine learning techniques on the data stored in the ontology to predict various trends about CSA uptake to date.

Data Set

CSA natural language statements (2021). Available from <https://drive.google.com/drive/folders/1y2BN2Maya3olPkumKPbps5qF5k0xXIMu>

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