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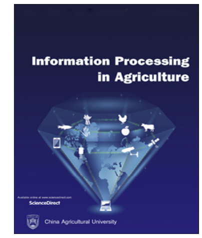

A survey of semantic web technology for agriculture

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ABSTRACT

Semantic web technologies have become a popular technique to apply meaning to unstructured data. They have been infrequently applied to problems within the agricultural domain when compared to complementary domains. Despite this lack of application, agriculture has a large number of semantic resources that have been developed by large NGOs such as the Food and Agriculture Organization (FAO). This survey is intended to motivate further research in the application of semantic web technologies for agricultural problems, by making available a self contained reference that provides: a comprehensive review of preexisting semantic resources and their construction methods, data interchange standards, as well as a survey of the current applications of semantic web technologies.

Contents

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1. Introduction

Agriculture and in particular precision agriculture is currently generating ever increasing volumes of raw data from sources such as: soil sensors, drones, and local weather stations. Raw data in itself is meaningless and isolated, and therefore may offer little value to the farmer. The usefulness of data comes from context and meaning, as well as its aggregation with other data sources. Semantic web technology can provide context and meaning to data as well as its aggregation by providing common data interchange formats, and data description languages.

Agriculture, due to initiatives from organizations such as the Food and Agriculture Organization of the United Nations (FAO) has a number of substantial semantic resources and data interchange standards at its disposal. But at the time of writing the application of semantic web technologies in agriculture is underutilized. The motivation of this survey is therefore to provide researchers who with a comprehensive resource that: provides a survey of the main semantic resources, details the main semantic data interchange standards as well as reviews the application of semantic web technology to agricultural problems.

The format of this review will adhere to the following structure: i. brief analysis of the literature review, ii. justification of agriculture as a suitable domain for semantic web technology, iii. review of the main semantic web technologies and data interchange protocols, iv. review the construction methodology of agricultural semantic resources, and v. survey the applications of semantic web technology.

2. Analysis of reviewed publications

The literature review conducted for this review considered articles that appeared in peer reviewed conferences, journals and books. The review process used academic indexes such as DBLP and Google Scholar. The key terms used were: “agriculture”, “semantic web”, “farming”, “agricultural”, “ontology”, “ontologies” and ”taxonomy” were used to gather an initial set of papers. The initial set of papers numbered approximately 200 papers. These set of papers were filtered against Beall’s list of predatory publishers[1] to remove any low quality publications. From this initial list an iterative process was followed where the articles that cited these papers were gathered. This process was followed until there were no new papers discovered. Each of these papers were read, and papers whose central theme was not: an agricultural semantic resource, an application of a semantic resource to a agricultural problem or a construction methodology for an agricultural semantic resource, were removed. In addition, any paper that was not peer reviewed was deleted, unless the paper was either: a technical report published by an academic institution, or a standard published by recognized bodies such as the World Wide Web Consortium (W3C).

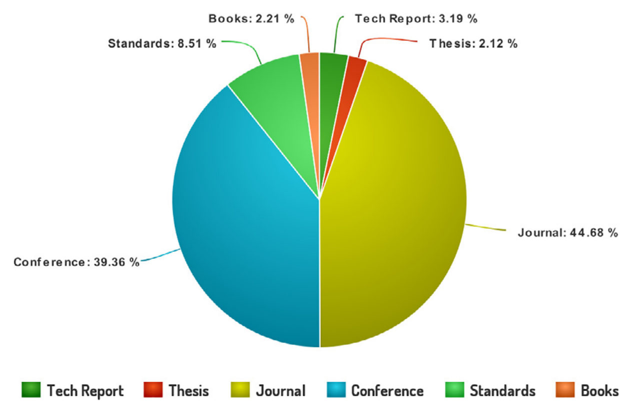

Fig. 1 – Publication sources.

The breakdown of the publication sources is shown in Fig. 1. The resource types are broken down into: Journal and Conference publications, Semantic Standards, Books, Technical Reports and PhD/MSc Thesis. Fig. 1 clearly shows that the majority of publications were published as either: journal or conference articles. The remaining sources (Thesis, Technical Reports, Books and Standards) accounted for approximately 16.00% of the publication sources.

The main publication source, journal articles, are not concentrated in a single journal, but are equally spread over a large number of journals. The Journal of Potato Research,[2]

[1] https://beallslist.weebly.com/.

[2] (https://link.springer.com/journal/11540).

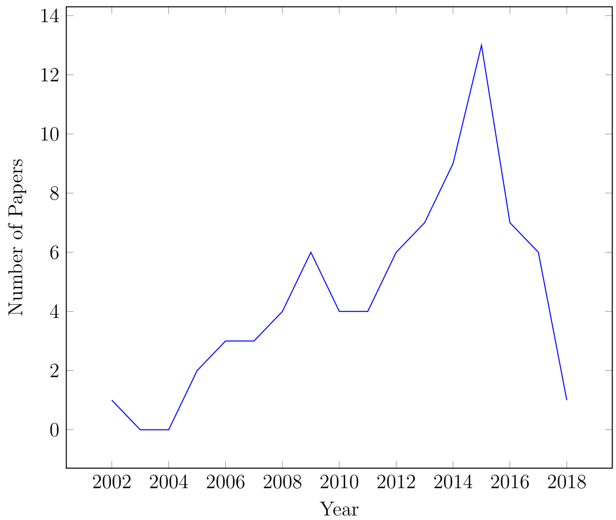

Fig. 2 – Number of semantic web technology research papers published by year.

International Journal of Metadata, Semantics and Ontologies,[3] and Computers and Electronics in Agriculture[4] were the only journals that furnished more than one paper.

A second simple analysis was undertaken which measured the yearly frequency of publication. The results shown in Fig. 2 demonstrate that the discovered papers have been increasing in frequency over time, however the number of papers that were discovered was relatively low when compared with other comparable areas, therefore the upward trend may be volatile. The research conducted could not find a causal driver of the upward trend between 2002 and 2014, and the drop in frequency of publication from 2016. It is however likely that the increase in publication may be due to the increase of availability of semantic resources for agriculture. The reason for the drop-off in publication is unknown, but it is an assertion of this paper that due to initiatives from Godan https://www.godan.info that will be an increase in publication in the near future.

The two analyses are meant to be a guide to the papers discovered for this literature review. It is possible that these graphs are representative of the field in general, but because of the relatively small number of papers involved this may not be the case.

3. Semantic web technology for agriculture

The term semantic web was coined by Tim Berners-Lee. His intention for the semantic web was to bring structure and meaning to information described in web pages [5]. This intention has been encoded into a World Wide Web Consortium (W3C) standard. Its stated aims are: "..... to create data stores on the Web, build vocabularies, and write rules for handling data." [92]. It is an assertion of this review that agriculture is a domain that is well suited for the adoption of semantic web technologies and this section will provide a basic justification for the adoption of semantic web technologies. It is assumed that the reader has some basic understanding of the semantic web and its associated technologies. Readers who are new to this area are encouraged to consult [100] for a detailed discussion of the area.

3.1. *Knowledge store*

Agricultural processes are dependent upon an interlinked body of knowledge. For example, the yield outcome of a crop not only relies upon the crop species, but also the soil composition, the local climate, pest populations as well as the severity of weed invasions. It is unlikely that any single knowledge base will contain all of this information at a sufficient granularity that would be useful to an individual farmer. This dependence upon knowledge from differing areas can be offset using semantic web technologies, because it is more likely that there will be isolated detailed stores on each of these domains, rather than a single monolithic knowledge base. Isolated stores of knowledge can be aligned using semantic web technology. This process will allow it to be queried as a larger interlinked resource of knowledge.

3.2. *Data integration*

Precision agriculture is becoming ever dependent upon data. Data flows from divergent data sources will need to be integrated so that they can be either queried as an aggregated data-flow or stored in a separate system for off-line processing. Semantic web technologies can provide a common structured representation of information gathered from real-time sensors as well as from non-real time sources such as producer and retail systems. Data integration is becoming one of the major issues in precision agriculture [102]. Consequently semantic web technologies are starting to play a more important role.

3.3. *Discussion*

Agriculture is beginning to be dependent upon data, therefore because of this dependence it is an assertion of this review that semantic web technologies has an important role to play in digital and precision agriculture because of its ability to represent and integrate data as well as infer new knowledge through the use of reasoners. These properties will be discussed later on in the article in areas such as Precision Diary Farming [88] and interruptions in food supply [64].

4. Semantic resources for agriculture

The adoption of semantic web technologies is dependent upon the availability of existing semantic resources. Semantic resources for agriculture are resources that use semantic technologies to describe knowledge collated by an organization or individual, and for the purposes of this survey the described resources are freely available, and come with liberal user licenses.

Semantic resources that were reviewed for this section included: controlled vocabularies, taxonomies, thesauri and

[3] (http://www.inderscience.com/jhome.php?jcode=ijmso).
[4] (https://www.journals.elsevier.com/computers-and-electronics-in-agriculture).

Table 1 – Summary of the domains of Ontologies and Thesauri, where GA = General Agriculture, CC = Climate Change, WR = Water Resources, C = Crops, P = Plants, A = Animals, F = Fungus, Ft = Farm Technology, P = Pests, Po = Potato.

Ontology Name	Domain								
	GA	CC	WR	C	P	A	F	Ft	P	Po
Agrovoc [22]	x									
Chinese Agricultural Thesaurus [54]	x									
THESAGRO [79]	x									
OntoAgroHidro [7]		x	x							
Crop Ontology [77]				x						
Cab Thesaurus [8]					x	x				
ITIS [43]					x	x	x			
GCP [78]				x						
AgroPortal [45]	x			x						
UC-ONTO [51]				x						
Agricultural Technology Ontology [42]								x		
Agronomic Taxon [74]									x	
Potato Ontology [37]										x

ontologies. Controlled vocabularies are simply a set of pre-selected terms or words for a specific domain [90]. A taxonomy conversely systematically arranges controlled vocabularies into a organized hierarchical structure which can be visualized as a tree. The meta-data about the entity is contained in its parents as well as the edge connecting it to its parent [90]. A thesaurus is similar to a taxonomy, but in addition to a hierarchical structure a thesaurus contains broader relationships where entities can be linked where they don't have a direct hierarchical relationship [90]. Ontologies are a way to "formally model the structure of a system, i.e.. the relevant entities and relations that emerge from its observation" [36]. This formal model is a graph where nodes are entities and edges between them describe the relationship between entities. Typically with ontologies, the designer can develop user defined classes which can have a finer granularity then generic categorizations that are used in taxonomies and thesauri [90].

Agriculture is well served by freely available resources, because there has been a concerted, but uncoordinated effort to develop semantic resources for agriculture by various national agencies [7,8,13,22,25,37,42,43,46,45,51,74,77,78,?]. Semantic resources are typically one of two types: general agriculture [22] or specialized sub-domains of agriculture.

4.1. *Overview*

The semantic resources discovered for this review covered a number of sub-domains of agriculture. There is a significant amount of overlap between the resources. A high-level overview of the areas covered by the semantic resources is demonstrated in Table 1. The repetition is most pronounced in General Agriculture and Crops where there are four resources for each. There was further duplication in the Pest and Animal domains.

The languages supported by the major agricultural ontologies and vocabularies is demonstrated in Table 2. It is clear from the table that English, Portuguese and Chinese are the most widely supported languages. It should be noted that the larger resources support multiple languages, whereas the smaller resources typically support one.

4.2. *Comprehensive semantic resources*

The largest and most comprehensive semantic resource, AGROVOC, [22], was developed by the Food and Agriculture Organization of the United Nations[5] (FAO). AGROVOC is a controlled vocabulary that contains 35,000 concepts and 40,000 terms. AGROVOC not only has terms and concepts about agriculture, but also contains information about: food, nutrition, fisheries, forestry and the environment. This spread of information covers the ambit of the FAO. AGROVOC is multilingual and is available in 27 languages including English, Arabic and Chinese. It supports the Linked Open Data Schema (LOS), and consequently AGROVOC has been aligned with a further 16 resources,[6] such as the Chinese Agriculture Thesaurus [54], and the National Agricultural Library's Agricultural Thesaurus [55] as well as related areas such as Environmental Applications Reference Thesaurus, and general non-related resources such as DBPedia [3].

The aforementioned National Agricultural Library's Agricultural Thesaurus (NALT) contains 128,253 agricultural terms in English and Spanish. The thesaurus has 17 subject headings such as: Farms and Farming Systems, and Rural and Agricultural Sociology. The thesaurus supports LOS, and has been integrated with not only AGROVOC, but other semantic resources such as Aquatic Sciences and Fisheries Abstracts (ASFA).

The Chinese Agricultural Thesaurus (CAT)[54] which is also aligned with AGROVOC contains 40 categories such as

[5] http://www.fao.org.

[6] A full list of integrated resources can be found here: http://aims.fao.org/standards/agrovoc/linked-data.

Table 2 – Languages supported by agricultural ontologies and thesauri.

Ontology Name	Supported Languages
Agrovoc [22]	Arabic, Chinese, Czech, English, French, German, Hindi, Hungarian, Italian, Japanese, Korean, Lao, Malay, Persian, Polish, Portuguese, Russian, Slovak, Spanish, Telugu, Thai, Turkish and Ukrainian.
Chinese Agricultural Thesaurus [54]	English and Chinese
THESAGRO [79]	Portuguese
OntoAgroHidro [7]	Portuguese
Crop Ontology [77]	English
Cab Thesaurus [8]	English
ITIS [43]	English, French, Spanish, and Portuguese
GCP	Not documented
AgroPortal [45]	Multiple, but precise languages not documented

crop classification and 63,000 concepts such as the Legume Crop and Azuki Bean Mosaic Virus. It also supports LOS, and has therefore not only been aligned to AGROVOC, but to other resources such as EUROVOC and LCSH.

Alignment between ontologies can be achieved through the computation of the textual difference between concept names from different semantic resources. Concept names that have the exact name are referred to as an exact match and concept names with small differences are known as a close match. The differences between an exact and close matches can be found at https://www.eionet.europa.eu/gemet/en/concept/9295 which describes the concept Western Europe which has extact matches in EuroVoc (http://eurovoc.europa.eu/913) and AGROVOC (http://aims.fao.org/aos/agrovoc/c_8364.html) and a close match in UMTHES (Westeuropa https://sns.uba.de/umthes/de/concepts/_00101238.html). The degree of alignment between AGROVOC and a number of semantic resources is described by [12], and a subset of the findings are summarized in Table 3.

The alignment of AGROVOC with other semantic resources both agricultural and non-agricultural is shown in Linked Open Data Map which can be found at https://lod-cloud.net/-clouds/lod-cloud.svg.

The integration of AGROVOC with NALT, and CAT demonstrates the original intention of a linked web of data. Not only is AGROVOC aligned with NALT and CAT, but implicitly aligned with EUROVOC and ASFA through CAT and NALT respectively. Consequently an individual can access the aligned resources as a single data source. This has implications for agriculture as individual resource developers who produce specialized resources can extend the major resources that use LOS such as AGROVOC.

4.3. *Ontology repositories*

AGROVOC is a large monolithic resource. There is, however, an alternative approach to large semantic resources, which is an aggregation of smaller ontologies into a larger resource. There were four significant resources located in the literature review. They are: The Crop Ontology [77], AgroPortal [45], CIARD Ring [65] and Vest.[7] These resources are typically accessible via a web interface and can be queried.

The Crop Ontology contains a large number of ontologies that can be searched by:"phenotype, breeding, germplasm and trait categories" [59]. The Crop Ontology provides a web interface that allows collaboration between users. The public facing web-interface is known as the Crop Ontology Curation Tool[8] which is an Open Source project that allows the sharing of ontologies. The aforementioned tools allow the uploading of trait dictionaries for crop breeding, and the direct creation of ontologies. The trait dictionaries have a Germplasm ID which is associated with standard variables that describe traits of a specific germplasm, such as yield and grain colour. Ontologies can be created via the upload of an OBO file that contains the RDF-triples for the proposed ontology. It is also possible to create an ontology via an interactive interface where terms and relations can be added manually.

The Crop Ontology has a public facing REST Web API, through which the various ontologies can be: queried, created, updated or deleted. Commands are appended onto the end of a URL, and the information is returned in a JSON format. A typical query is: http://www.cropontology.org/get-ontologies, which returns a list of available ontologies.

The AgroPortal [45] is similar to the crop ontology as it contains 98 ontologies and thesauri which can be queried through a web interface. The web interface allows a user to enter a search term and the requisite annotations are returned from the matched ontologies. It is possible to return the data in either: JSON or RDF. AgroPortal also has a REST Web API similar to The Crop Ontology.

The Crop Ontology and AgroPortal are superficially similar, there are however there are some differences. The main one is that AgroPortal contains non-crop ontologies such as the Animal Disease Ontology (ADO) and the Biorefinery (BIOREFINERY) Ontology.

The CIARD Ring portal [66] is an index of vocabularies and semantic web services. At the time of writing CIARD Ring portal had 3201 datasets, and 5327 data services. In addition to semantic resources and services, CIARD Ring portal indexes a number of software tools to parse semantic resources.

The Vest repository, which is held by both the FAO and Godan, is a comprehensive list of semantic data resources. It has 398 resources, as well as a graphical overview of the alignment of semantic resources. In addition to the list of semantic resources, Vest also has a RDF query interface where all of the aforementioned semantic resources, can be queried using SPARQL. SPARQL commands can be issued directly through a webpage or via a REST WEB API.

The advantage that repositories have over their larger cousins such as AGROVOC, is that development is decentralized. Specific or specialized information that may be of interest to a small number of users that may be ignored by the larger ontology developers can be added by a motivated individual to an ontology repository. An example of this phenomena is

[7] http://vest.agrisemantics.org.

[8] https://github.com/bioversity/Crop-Ontology.

Table 3 – Summary of Aligning Matches with AGROVOC [12].

Resource	Area	Lang used for Link Discovery	Number of Matches
EUROVOC	General	EN	1297
NALT	Agriculture	EN	13,390
LCSH	General	EN	1093

that AgroPortal contains the FoodOn Ontology[9] which describes not only the country of origin of food, but its wrapping and preservation process as well as a number of other meta-properties. It is likely that this fine-grained information will be missing from the larger ontologies.

4.4. *Linked data hubs*

Berners-Lee's initial vision of the Semantic Web was for an interconnected web of data. Semantic resources for agriculture can also interlinked with linked open data [6]. It is possible to create linked data hubs that act as a bridge to link together disparate semantic resources. One significant resource may become a hub by default because content providers align their smaller resource with the main resource [48].

A complementary approach is to build a mapping scheme that explicitly aligns selected semantic resources. This is the approach that the designers of Global Agricultural Concept Scheme Core (GACS) [4] took. The stated aim of GACS is to: "improve the discoverability and semantic interoperability of agricultural information and data" [4]. GACS achieves these aims by linking together major resources such as AGROVOC, the CAB Thesaurus and the NAL Thesaurus which in turn map to "datasets about food and agriculture." [4].

The architecture of GACS is organized by thematic groups which are arranged in a hierarchical structure. The top level thematic groups are: "General, Physical Sciences, Earth Sciences, Life Sciences, Applied Science and Technology, and Social Sciences and Humanities" [4]. There are 145 s level groups, and the Agriculture, Fishery, and Forestry thematic group comes under the Applied Science and Technology top level group. The concept hierarchy is a known source of weakness,[10] because the concepts are often inconsistent.

The thematic groups contain related concepts from AGROVOC, CAB and NAL. The thematic groups cover about 82% of the concepts from AGROVOC, CAB and NAL [4]. The concepts in the base resources that have no direct equivalent in all of the base resources are aligned using custom relations specific to GACS [4].

Although GACS is the largest attempt to unify concepts from individual resources, there are other attempts to unify divergent semantic resources. For example, LusTRE [1] links together a number of environmental semantic resources such as: EUNIS (Species and Habitat types), and Environmental Application Reference Thesaurus (EARTH). The resources that are contained within LusTRE are also integrated through Linked Data to agricultural resources such as AGROVOC and NAL. LusTRE also has a "human readable interface" [1] that allows users to query the linked resource. In addition to GACS and LusTRE there are linked data hubs that have integrated specialized semantic agricultural resources such as soil [50], and land administration [9]. The interoperability of semantic resources through the use of Linked Data is often referred to agrisemantics (http://agrisemantics.org), and Linked Data Hubs can be seen as first step for the agrisemantics movement's aim of interoperability between semantic resources for agriculture.

4.5. *Semantic data standards*

Agriculture requires common standards for semantic web technologies to enable the free exchange of semantically described data and the development of common vocabularies. The FAO has attempted to produce such a standard for: "the description, resource discovery, interoperability and data exchange for different types of information resources" [27]. This standard is known as: The Agricultural Metadata Element set (AgMes). The AgMes standard consists of five separate sub-standards, which are: "AGRIS Metadata (AGRIS AP), Event Metadata (Ag-Events AP), Job Vacancy Meta-data (Ag-Jobs AP),Learning Resources Metadata (Ag-LR AP) and Organization Metadata (Ag-Org AP)" [27].

Arguably the most important sub-standard in AGRIS is the Metadata Application Profile (AGRIS AP) [32]. AGRIS AP draws elements from Dublin Core [49] and the AgMes namespace [28]. It does not define new elements, but defines the data types as well as their cardinality [28]. The subject classifications and terms are defined by external standards and vocabularies such as AGROVOC, and AGRIS Subject Categories.[11] The AGRIS Subject Categories have a number of categories outside of agriculture such as: Geography and history (B, B10, B50) and Education, Extension, and Advisory work (C, C10, C20, C30). However the majority of the subject headings are directly related to agriculture.

The research literature review failed to locate any competitors to AgMes. The lack of competitors could be due to the comprehensiveness of AgMes. The AgMes standard is probably the standard for semantic technologies for the immediate future.

4.6. *Data exchange*

As stated earlier, data exchange is having a more important role to play in agriculture. Data exchange is possible with semantic web technologies because exchange of semantic

9 http://foodon.org.

10 http://aims.fao.org/fr/activity/blog/gacs-structural-survey-and-hierarchy-scenarios.

11 http://www.fao.org/scripts/agris/c-categ.htm.

data can be achieved through the use of an agreed standard between the transmitter and the receiver of information. Pre-existing semantic resources, as well as AgMes, can be used for data exchange because they have publicly available schema which both the transmitter and receiver of the data will have access to.

Semantic resources are not primarily designed for data exchange, there are, however standards whose principal objective is data exchange. One such standard is AgroRDF [58] which is a data exchange standard designed specifically for agricultural data. AgroRDF is a semantic overlay for AgroXML [58] which is an XML data exchange standard. Its stated aims are:"exchange between on-farm systems and external stakeholders, high level documentation of farming processes, data integration between different agricultural production branches, semantic integration between different standards and vocabularies and means for standardized provision of data on operating supplies" [29]. The AgroRDF standard was unique in the literature review, as other data exchange standards were primarily designed to be semantic resources rather than an overlay for an XML standard. AgroRDF was the data exchange protocol that was used in the iGreen project [35] which was an attempt to give German farmers access to decision support information [35].

The AgroRDF standard is designed for farm work, whereas AgriOpenLink is an approach to semantic data integration for farm equipment. It was proposed by [89]. AgriOpenLink architecture has a: Semantic Service Repository and a Service Registration/Invocation modules. The Semantic Service Repository module allows developers to annotate and publish service descriptions. The annotation for the services described in Semantic Service Repository module used Semantic Annotations for WSDL and XML Schema (SAWSDL) [30]. This standard mandates that the annotations of the services reference a concept in an ontology, and in this way the annotations are undertaken in a systematic manner which is determined by an ontology. The standard does not determine the implementation language of the ontology.

The client services are run directly on the machinery, and are registered with the Service Registration/Invocation module which in turn references the Semantic Service Repository. The client service communicates with the Service Registration/Invocation module to invoke the service on a remote machine. The client service communicates data that has been generated by the machinery. This data is then analyzed by an undescribed data analytics service.

A concrete use case of the application of AgriOpenLink is given by [88]. They present an example of its use in Precision Dairy Farming. The case study used AgriOpenLink as a "data integration and decision support platform for adaptive process control" [88]. The case study used the Dairy Farming Ontology (DFO) [88] to integrate the various data sources by providing a common vocabulary for the data providers to abide by. In addition the DFO acts as a knowledge base against which users can query the generated data. The data generators are client services that run on diary farming equipment such as: "automatic milking machines, concentrate feeders, and heat and activity monitoring equipment" [88]. The data is aggregated and stored. This stored data is then queryable by SPARQL. The authors describe typical queries as queries that identify lame cows or second lactation.

Data exchange is possible with semantic web technologies and will be become increasingly more important as mechanization of farms increases and the use of remote sensing technologies become more popular. This is because the disparate systems will have to communicate with a central system and on occasion with each other.

4.7. *Discussion*

There are a relatively large number of vocabularies or ontologies for the semantic web of agricultural data. The agrisemantic community is following the ethos of the semantic web by aligning the larger resources such as AGROVOC and NAL and aggregating the smaller resources in online platforms. In addition to the alignment of semantic resources, AgMes can be used to link the meta-data elements it defines to controlled vocabularies. There are some exceptions to the linking endeavours, and there are some significant standalone resources such as Thesagro [79] for Brazilian-Portuguese.

Large comprehensive semantic resources can be labour intensive and expensive to construct, consequently these types of resources are limited to large and well funded organizations such as the FAO. It is therefore likely that the future of the development of new semantic resources will follow the model pioneered by The Crop Ontology, where specialized ontologies will be created on an ad hoc basis, and will be made available to the general community via an online platform. These aggregated resources will offer finer-grained semantic information that is currently missing from the larger resources.

Agriculture, despite the lack of a W3C specification has a large number of pre-defined ontologies and vocabularies. Because of the size of AGROVOC, and the number of resources it has been aligned with, it should be considered to be a de facto semantic standard for agriculture.

5. Creation of agricultural semantic resources

Although there are a substantial number of semantic resources for agriculture on occasion semantic web technology researchers may wish to develop new specialized resources outside the collaborative editing platforms of the Crop Ontology and AgroPortal.

The research literature describes two distinct approaches to the creation of agricultural centred semantic resources. The two approaches are: construction of a new semantic resource [18,53,56,71,73,83,93,94,96,101,103] and merging of existing semantic resources [2].

5.1. *Creation of new semantic resources*

The creation techniques for new semantic resources typically consist of the creation of agricultural ontologies rather than thesauri. The main approaches for the construction of agricultural ontologies that are described in the research literature are: manual [18,103,18,96], automatic [71,73] and semi-automatic [56,83,101].

The manual approaches tend to rely upon a domain expert or group of experts to create the ontology. The manual approaches found in this review did not have a coordinator to guide the information elicitation process. The surveyed strategies were an ad hoc construction process. This uncoordinated process approach must cast doubt upon the accuracy of the resultant ontology. In addition the discovered strategies favoured collaborative editing platforms that allow a group of experts to work on a single ontology. These approaches are arguably similar to the tools provided by the Crop Ontology and Agroportal.

An alternative manual construction process is to use stakeholders rather than experts. Stakeholders are individuals who have a vested interest in the result of a project that uses the proposed ontology. Stakeholders may have knowledge that is not be captured in an ontology designed by experts. This is the approach used by [94]. They used stakeholders to elicit information about problems during the farming cycle. This information was integrated with information gathered from subject experts and from preexisting knowledge bases.

A flaw in the manual approach is that the construction of a substantial resource is a labour intensive process which may not yield a comprehensive resource, because of gaps in knowledge in any group of stakeholders or experts. The alternative to a manual construction process is to construct semantic resources from existing data or knowledge bases. Automatic approaches discovered in the literature review constructed ontologies from textual resources. These approaches normally rely upon extracting relations from textual data. The extracted relations represent relationships between entities in text. These relationships are aggregated and transformed into an ontology.

Relations are often extracted using a pattern based information extraction strategy. The rationale behind this approach is that it will have a high precision, but typically has a lower recall than its machine learning counterpart. A common extraction pattern used in the literature is subject verb object, where the subject and object represent the subject and object from an RDF triple, and the verb is the predicate which describes the relationship between the subject and object. The flaw in fully automatic construction methodologies is that relation extraction techniques will make errors, and there will be mistakes in the base material. If errors are left unchecked then the resultant ontology can be overwhelmed by errors [24].

There were relatively a small number of papers that used a fully automatic approach. The strategy described by [71] is representative of the area. Their approach constructed an ontology by converting AGROVOC to an ontology and enriching its relations with a relation mining technique that extracted relations from a relevant corpus. This approach reduces the possibility of errors from a relation extractor by restricting relation mining to concepts defined within AGROVOC.

Semi-automatic approaches to semantic resource construction can mitigate the flaws of fully automatic and manual approaches by combining an automatic relation extraction step, and a manual refine phase. The approach described by [101] is typical. They describe a semi-automatic approach which created The Pest Ontology. Their approach extracts meta-data from the web pages which is then refined by human experts to create The Pest Ontology. The meta-data extraction step parses relevant web pages to extract relations using a pattern based approach. It is not clear from the paper which extraction patterns were used. The relations are then mapped to a preexisting ontology structure. The design of the ontology is also missing from the paper. The consistency of the Pest Ontology is validated with a reasoner, and the information that the ontology contains is then checked by a domain expert.

5.2. *Merging existing semantic resources*

The construction of semantic resources from scratch, whether manually or automatically, can be an error prone process that does not produce the desired resource. An alternative construction approach is to merge existing resources. This is the approach favoured by [2] who describe a technique for merging non-ontological information sources into a single agricultural ontology. Their approach depends upon the Neon Ontology Construction Methodology [81]. The Neon Ontology Construction Methodology consists of nine scenarios that provide guidance to the ontology engineer to reuse existing resources to create a new semantic resource. The merging process proposed by [2] used Neon scenario seven. Neon scenario seven describes a technique for using design patterns to build ontologies [70].

Their approach has three steps: manual selection of relevant resources, transformation of the non-ontological resources into the Web Ontology Language (OWL) and the merging of the aforementioned resources into a single ontology. The manual selection step involves a domain expert and an ontology engineering technician to select which sources to integrate. At this stage the sources selected in the first step have been transformed into OWL. The final step is the merging process, which itself has three sub-steps: mapping, trust computation and filtering. The mapping step identifies alignments in all of the candidate sources identified in the manual selection of relevant resources step. The trust computation step computes a trust score for the alignments identified in the mapping phase. The trust score is assigned by identifying the number of separate knowledge base the alignments are members of. If the alignment is not a member of two or more knowledge bases it is removed.

Merging existing resources to produce an extended or enriched semantic version is a technique that has the lowest barriers to entry, and is an efficient technique for researchers without access to manual annotators or editors. Agriculture has a large number of semantic resources and therefore a merging strategy is a suitable technique for agriculture to create quasi new agriculture semantic resources.

5.3. *Agricultural semantic resource evaluation*

Semantic resources that are created using any of the previously discussed techniques will need to be evaluated to ensure that the relationships and the concepts that they contain are correct. Evaluation could be done manually, but that could be an labour intensive process for larger ontologies.

Manual evaluation is typically undertaken by experts and not by the users [101]. An alternative to a manual approach is an automated approach that uses software tools that detects flaws in the ontology. Automated approaches can only detect errors in the organization of the ontology, but not its contents.

An approach described by [95] uses a combination of manual evaluation of content of an ontology, and an automated tool to evaluate its structure. The manual evaluation followed the Delphi Technique for gathering expert feedback, and the OOPS! validation tool [69].

The Delphi technique [39] is a data gathering technique that attempts to identify "convergence of opinion on a specific real-world issue" [39]. The technique achieves this through questionnaires and an iterative process that allows participants to refine their answer based upon feedback from the process organizers. This process continues until a consensus is found. OOPS! Web-based tool [69] is a tool that validates ontologies through the validation against a pitfall catalogue. The pitfall catalogue contains 41 pitfalls.[12] The pitfalls in the catalogue are grouped into four categories: human understanding, logical consistency, real world representation and modelling issues [69]. The tool has a secondary check that validates if the OWL is consistent. And finally the tool provides a suggestion scanner that identifies "properties with equal domain and range axioms and proposes them as potential symmetric or transitive properties" [69].

The approach proposed by [69] was exception in this survey, because the majority of the papers discovered in the literature review either used manual validation or had no validation of the semantic resource. This trend of limited or no validation calls into question the quality of the resource, and its applicability to the applications that are dependent upon the information the resource contains. Although a detailed discussion of semantic resource evaluation is beyond the scope of this review, interested readers can consult [86] for a thorough investigation of the area.

5.4. *Discussion*

The agricultural domain has a number of comprehensive existing vocabularies, and ontologies. In general the creation of new resources should be avoided because the existing semantic resources provide an in-depth as well as a broad coverage of agriculture.

It is possible that small specialized ontologies may be required for a specific sub-domain of agriculture, and in this situation a manual approach must be followed using stakeholders or domain experts. A flaw in the surveyed manual approaches was that they did not follow a recognized ontology construction approach. A systematic approach which follows a pre-defined ontology engineering methodology such as [84] will produce ontologies that accurately represent the domain knowledge of domain experts or stakeholders.

If there is a need to construct larger resources that cover areas of agriculture that are not represented in current resources a merging of non-semantic resources into a semantic resource as proposed by [2] is recommended because the technique computes a trust rating of the underlying resources which can be extended to the constructed resource.

If it is not possible to use the aforementioned techniques then it is a recommendation of this survey to use semi-automatic strategies or if it is necessary to use automatic techniques then it should be guided by a preexisting comprehensive resource. Unguided automatic construction methods should be discouraged because semantic web resources in agriculture must be considered as a gold-standard, and a large number of errors will have an impact upon applications that rely upon it.

It is also a recommendation of this survey that unless there is a pressing need, the construction of unique resources that do not use: Linked Open Data, or are created outside of the Crop Ontology or AgroPortal platforms should be avoided, because they will be isolated, which was not the original intention of the semantic web.

6. Applications of agricultural semantic technologies

Semantic web technologies and their resources can be integrated into applications. The literature review considered applications that are dependent upon semantic technologies and were designed directly for the agricultural domain. The literature review revealed a number of frequent areas of agriculture where semantic web techniques have been applied. The main categories of application are: Knowledge based systems [16,17,44,52,53,82,94], Remote Sensing [40,47], Decision Support [14,15,23,33,34,61,63,64,67,72,80,93,98,99] and Expert Systems [11,26].

The frequency of publication is shown in Fig. 3, and is quite clear that decision support is the most frequent area of research.

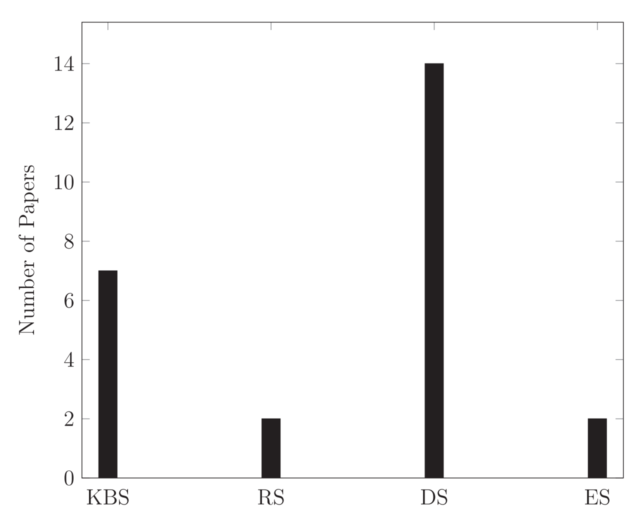

Fig. 3 – Popularity of research areas, where KBS = Knowledge Based Systems, RS = Remote Sensing, DS = decision support and ES = Expert Systems.

[12] The catalogue can be found here http://oops.linkeddata.es/catalogue.jsp.

6.1. *Knowledge based systems*

Knowledge based systems are applications that reason with information that is stored in a knowledge base to solve complicated problems. The papers that were selected from the literature review used an ontology or related semantic technologies to store knowledge as concepts and their interrelationships. The most popular application areas within the knowledge based systems are: Question-Answering [44,17,75,60,91] and Semantic Information Retrieval [52,94,97,10,76].

Question-Answering systems in the agricultural domain allow the user to pose questions about agricultural related issues. The user then receives the answer in natural language. A typical example of a Question-Answering system was developed by [17]. They describe their system as an "Advisory System for Cotton Crop" [17] for the Gujarat region that is located in India. The system allows the user to pose questions about surrounding farms, plant diseases and pest infection. The system is aimed at smallholders,[13] consequently users can pose questions via a mobile phone. The system contains three parts: Cotton Ontology, Web Service and Mobile Application.

The Cotton Ontology contains information that represents events and agents, such as disease and pest information, that affect the cotton crop in the Gujarat region of India. The web service allows users to query the Cotton Ontology via the mobile application. In addition to the Cotton Ontology, the advisory system has access to open data such as weather that can be used to augment the information in the Cotton Ontology.

The system demonstrates the application of semantic web technology for small scale farmers in low income countries. The ubiquitous availability of mobile phones allows small scale farmers to access critical information which will affect their crop. The impact of these low cost systems is likely to be significant because of the number of farmers that can access the described system is relatively high.

Information retrieval systems are simpler versions of their question answering cousins. This is because information retrieval systems typically rely upon keywords to return information that is related to the query. Ontologies can assist information retrieval systems in two ways: keyword expansion, and knowledge storage. Keyword expansion increases recall by adding semantically related keywords which are generated from the initial keywords. Knowledge storage is simply where the semantic resource contains the information that the user wishes to access. Information retrieval systems in agriculture are typically designed to return technical information about crops, pests and so forth.

The system designed by [52] is typical of agricultural information retrieval systems. This system uses an ontology about under-utilized crops. The system uses a web interface which users can query via keywords or browse by concept hierarchy. The results are displayed within the web interface.

The systems described in this section are similar in nature, in that they provide information based upon an initial query or question. The systems typically are designed for either local or specialized information that is generally not available on more general search engines. The use of mobile devices opens these systems to smallholders in less developed countries.

6.2. *Remote sensing*

The need for data integration, particularly from remote devices has already been discussed. The process of data integration can be eased by ensuring that the sources from which the data is drawn from is described in a semantic language and conforms to a preset standard and that the sensors meta properties are also described in a semantic language.

The agricultural domain is increasingly using remote sensing to gather data such as weather and soil pH from farms. This information can be used to infer future crop health [62].[14] And there is an effort by Semantic Sensor Network Incubator (SSNI) group to set a W3C standard for semantic web technologies.[15] The application of semantic web technologies to remote sensing is often referred to in the literature as the semantic sensor web.

The main contribution of the SSNI group was the development of The Semantic Sensor Network Ontology (SSN) [19]. The aim of the SSN is intended to standardize the semantic descriptions of sensors through the use of concepts related to sensors, actuators and observations. SSNI group explicitly stated that agriculture is one of the intended uses of the SSN ontology.

The SSN is typically used for sensor discovery and property discovery rather than describing the data that is transmitted by the sensor. The AgOnt ontology, however, is designed as a vocabulary for transmitted data from sensors [40]. It contains five top level concepts: product, phase, time, location and condition [40]. Each of these concepts have sub-classes that represent related agricultural concepts such as Seed, Seedling, Plant, Crop and Processed food [40]. The ontology allows the transmission of data in a uniform format from multiple sensors.

The sensor web applications allow the querying and drawing inferences from large sensor webs [41]. This ability to construct and query large ad hoc semantic sensor networks may assist farmers by providing real-time input into decision support systems. A use case for semantic sensor networks for 'smart farms' was argued by [31]. Their paper described a hypothetical smart farm, Kirby Smart Farm, which has 239 hectares and located in Australia. The farm has a hypothetical "100 soil sensors, two weather stations and 65 cattle tags" [31]. The author describe a hypothetical system architecture as well as mock-up of a management system that queries the sensor network. The management system alerts the user on a number of pre-defined events such as: "sowing time for a crop, cattle not in farm" [31].

Although there has been an attempt to standardized semantic sensor web ontologies by the SSNI there are a number of competing ontologies for semantic sensors. A comprehensive survey of the semantic sensors is given by [20] who

[13] http://www.ifpri.org/topic/smallholder-farming.

[14] A detailed discussion of the area is given by [62].

[15] https://www.w3.org/2005/Incubator/ssn/wiki/Main_Page.

compare competing ontologies for semantic sensors, as well as sensor concepts that are not represented in the main sensor ontologies.

The semantic sensor is a popular research area. And it is likely to increase in importance as the adoption of remote sensing techniques becomes more popular in agriculture and other related areas [21].

6.3. Decision support

Decision support systems is the most frequent area of research for semantic web technologies. This interest from the research community is likely due to the ability of semantic web technologies to represent knowledge which decision support systems are reliant upon. The systems discovered for this review covered Food Security [63], Crop Management [16], Pest Management [23], Irrigation [98], Crop Planning and Production [33,34,38,57,68,93,99], Food Production [15,61,64,87] and General Agricultural Production [67].

A frequency of publication of sub-areas of decision support can be found in Fig. 4, and it is clear from the figure that crop planning and production is the most popular sub-area of research.

There are two distinct types of systems that were discovered in the literature review. The most popular type of system was for individual farmers. The less frequent system were developed for governmental agencies so that they could model the effects of hypothetical shortages of specific crops or food. A typical system for this type was developed by [64]. This system allowed for the simulation of multiple scenarios caused by milk production failures. The generation of these hypothetical situations allows decision makers to evaluate the effects of their policies to mitigate the effects of milk shortages. In common with the majority of the decision support systems surveyed semantic web technologies were used as a knowledge store.

As for the systems that were developed for non-governmental agencies the two most frequent areas of decision support were: Crop planning and production [33,34,38,57,68,93,99] and Food Production [15,61,64,87].

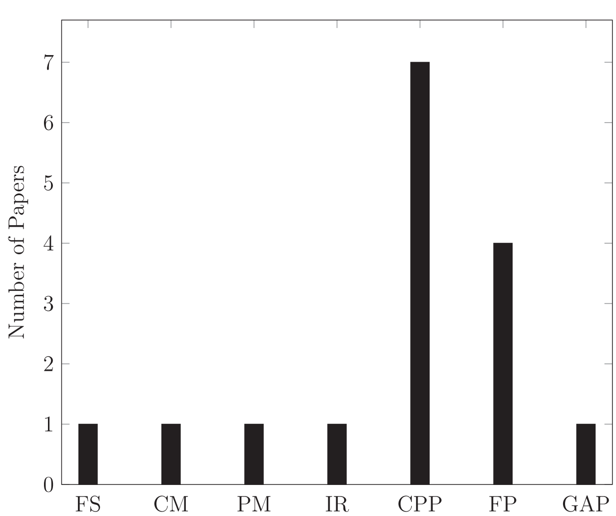

Fig. 4 – Popularity of research areas, where FS = Food Security, CM = Crop Management, PM = Pest Management, I = Irrigation and GAP = General Agricultural Production.

The crop production systems typically provide users with actionable information which they can use to mitigate crop losses. This is the approach favoured by [33]. Their system monitored information about "crops, pests, diseases, land preparation, growing and harvesting methods" [33]. They used an ontology created by aggregating information supplied by stakeholders to convert this information into actionable information which stakeholders accessed via mobile phones. The aggregated information from user interaction can be used as actionable information for government agencies. The authors provide an hypothetical example of "agricultural yield for the season" [33] as a use of aggregated information, but they do not provide any concrete case studies where aggregated information from users has been used.

Food production decision support systems that are used to: control, manage, or assist, in the direct production of food. The role of semantic web technologies was to act as a knowledge base or assist in the integration of data sources. The systems in this sub-category covered systems that supported the production of: wine [61], milk [64] and rice [15,87].

The system developed by [61] is an exemplar of the systems in this category. The system was designed to assist wine producers to make informed decisions about the traceability of wine, and the influence of irrigation practises upon the glutathione concentration in the final wine product. The glutathione concentration may affect the final quality of the wine. The ontology's role in this system was to facilitate data integration of disparate information sources. The authors created a new ontology for their system by merging "AEO (Ontology for Agricultural Experiments) and OFPE (Ontology for Food Processing Experiments)" [61]. The AEO is an ontology that represents concepts relevant to agricultural experimentation such as: agricultural input, agricultural activity and agricultural experiment.[16] The OFPE is an ontology that represents generic operations for processes that turns raw materials into a food product.[17] The aggregated ontology contains 136 concepts that describe wine making practices, operations and products [61].

6.4. Expert systems

Expert systems are computer systems that make decisions similar to humans based upon a reasoning process of available information. This category generated the least amount of papers. The expert systems that were discovered were developed to identify crop diseases [11,26]. These systems typically infer a disease based upon observations of a crop sample. In these systems an ontology operates as a knowledge base from which inferences can be made.

A representative system that was discovered in the literature review is [11]. The system is used to assist farmers to diagnose diseases that affect the maize crop. The system uses a domain ontology which has three main concepts: Plantation ontology, Disorder ontology and Observation ontology [11].

[16] http://agroportal.lirmm.fr/ontologies/AEO.
[17] http://agroportal.lirmm.fr/ontologies/OFPE.

The plantation ontology describes concepts that directly describe the plant environment [11]. The disorder ontology describes all the diseases that can affect each crop species, and the observation ontology represents the symptoms that can affect each crop species. The system also contains: a Problem solver editor, Concept editor and a Domain model editor. The inference process initially determines the plant growth stage then predicts the likely disease.

6.5. *Discussion*

The semantic web is an underutilized technique in agricultural informatics. There are relatively few applications in the research literature that use semantic resources to resolve agricultural problems, despite there being a large number of resources specific for agriculture.

Among 25 application papers discovered in the literature review all but one system used custom built domain ontologies. The exception was [67] which used AGROVOC. The ontologies hold information (assertions) that are used in the application that queries them. Ontological reasoners can infer new information from the original assertions, and in addition ontologies describe the relationship between entities. These characteristics arguably make semantic web strategies suitable for agricultural problems. Despite this suitability, and the low barrier to entry, there were as previously stated, relatively few research papers found in the literature review. There is no obvious explanation why there is such a dearth of research papers, but this lack of research makes this area a suitable target for further research.

7. Conclusion

Agriculture has a significant number of semantic resources. These resources are an ad hoc collection of vocabularies, ontologies and thesauri. Large and comprehensive resources have been integrated through linked data hubs or common vocabularies. Additionally, these resources are free and open. It is therefore surprising that the adaptation of these technologies in the academic literature is limited when compared to complementary domains such as bio-medicine. There may be an underestimation of the use of semantic web technologies in agriculture, because projects in the private sector that use semantic technologies are often not published in the academic literature. Nevertheless, the lack of published application of semantic web technologies in the research literature is concerning because it implies that there is lack of progress in publicly available research. The lack of published research may impede the yield gains that is predicted by the application of digital agriculture techniques [85]. It is hoped that this survey will stimulate further research into the application of semantic web technologies for agriculture.

7.1. *Future direction of research*

It is an assertion of this survey that the application of semantic web technologies for agriculture research can advance rapidly by co-opting strategies from similar fields. Therefore, this review proposes that knowledge discovery, and decision support using semantic web technology are the sub-areas in which existing techniques from complementary areas can be applied quickly and realize research advances in the immediate future.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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