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An Ontology-Based Automation System:
A Case Study of Citrus Fertilization

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ABSTRACT

This paper presents an ontology-based approach to benefit automatic fertilization management for citrus orchards located in mountainous regions. The core of the fertilization approach is the citrus fertilization ontology that covers knowledge about citrus fertilizers and fertilization application. Specially, the approach can provide not only the yearly fertilization quantities of required pure nitrogen, phosphorus, and potassium according to their disease symptoms, but also the suitable fertilizing recommendations for the citrus orchards with different soil properties. The current version of the ontology (ver. 2.9.10) contains 103 classes, 34 properties, 800 instances, which are defined by 3056 RDF triples and is evaluated by using 90 competency questions. Furthermore, the authors run experiments with the proposal targeting at four citrus orchards in Chongqing and compare its outputs with the reference values advised by the agri-professionals of citrus planting.

KEYWORDS

Automatic Fertilization, Bayesian Network Extension, Citrus Fertilization Ontology, Citrus Planting, Semantic Web

1. INTRODUCTION

Citrus is the main cash crop in Chongqing, China. According to the official statistics, the total citrus planting area in Chongqing reached 198, 200 (hm^2) and the yield was 2680, 000 (t) in 2018 (Zhao, 2019). As Chongqing is a mountainous region and most of citrus orchards located in hills, citrus production management is crucial for the quantity and quality of citrus yield. Domain knowledge plays a critical role in guiding the production management for citrus orchards that have complex soil and terrain conditions (Wang et al., 2016). In recent years, information technology (IT)-based systems have been widely studied in agricultural domain, with the aim to improve the efficiency of filed management (Wang et al., 2015; Santos et al., 2019). Then, a number of automation systems have been introduced including automatic irrigation and fertilization machines, and automatic growing

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and harvest machines for saving labor and boosting agricultural production efficiency (Partel et al., 2019; Sulistyo et al., 2017; Berenstein & Edan, 2017).

The main shortcoming of these agricultural automation systems is lack of sufficient domain knowledge, which is critical essential in decision support systems for realizing high-quality crop production management. In other words, agricultural systems are knowledge-intensive IT systems that need complex and even cross-area domain knowledge to help local farmers, who usually have limited domain knowledge, to make reliable decisions. Due to their knowledge modeling and reasoning capabilities, semantic technologies, including a set of semantic standards and ontology models, have achieved successes in many agricultural fields (Santos et al., 2019; Haverkort &Top, 2011; Beck et al., 2009). For example, Haverkort and Top (2011) created a potato ontology, a controlled vocabulary of the potato domain, to support automated decision making and data exchange. Beck et al. (2009) modeled soil, water, and nutrients for citrus and sugarcane based on ontology and implemented an ontology-based simulation environment. Wang et al. (2015) have developed an ontology-based application that realized fertilization, nutrition-related disease diagnosis, and water monitoring for citrus orchards. However, ontologies used in these systems were simple and at the vocabulary level (Vrandečić, 2004), which were insufficient for making a complicated decision.

With respect to the issue of automatic fertilization in citrus planting, however, the relevant semantic-based decision systems do not exist. That is to say, applying the technique of ontology to transparently and efficiently generate helpful decisions to carry out corresponding fertilization activities in citrus cultivation has not been found in the published literature. Then, we present an ontology-based fertilization system for citrus orchards, and it currently focus on the orchards located in mountainous regions of Chongqing. To the best of our knowledge, current fertilization systems can only suggest quantities of pure nitrogen (N), phosphorus (P), and potassium (K) for citrus trees, but fail to provide specific fertilizers for citrus trees planted in different orchards with various terrain and soil conditions.

In this paper, we create a citrus fertilization ontology (CFO) for citrus planting, which contains 103 classes, 34 properties, 800 instances, and 3056 resource description framework (RDF) triples. After that, we extend the CFO with Bayesian network (BN) to classify citrus trees into specific type of nutrition-related diseases (NRDs) according to their symptoms, to benefit making proper fertilization decisions in different scenarios. Finally, we develop a fertilization system to calculate the quantities of specific types of fertilizers at different growth stages of citrus trees in citrus planting.

The rest of the paper is organized as follows: in Section 2, the related work is discussed; Section 3 describes the citrus fertilization system including the design of the ontology and the fertilization management based on the CFO; Section 4 evaluates our system and presents a prototype fertilization machine. At last, we conclude the paper and outline the future work in Section 5.

2. RELATED WORK

There are a number of related studies focusing on automation systems for farm management, agricultural ontologies, and ontology-based agricultural systems respectively. We will discuss them with their categories.

Agricultural Automation: the automatic agricultural approaches and systems are generally proposed to save the labor cost in agricultural production (Partel et al., 2019; Sulistyo et al., 2017; Berenstein & Edan, 2017). To be specific, Sulistyo et al. (2017) proposed an approach based on deep learning to estimate nutrient contents in wheat leaves by analyzing color features of the leaf images captured on field with various lighting conditions. Berenstein and Edan (2017) designed an accurate pesticide-spraying device for pesticide management, which has a single spray nozzle with an automatically adjustable spraying angle, color camera, and distance sensors. Partel et al. (2019) developed a low-cost drip irrigation controller powered with battery for citrus orchards located mountains. The controller was designed to improve drip irrigation management efficiency and reduce the labor inputs.

Agricultural Ontologies: the agricultural ontologies are normally development based on the semantic technologies since such technologies can better manage the complex and even cross-area domain knowledge in agricultural production. Specifically, Food and Agricultural Organization (FAO) developed the AGROVOC[1], which is a multilingual vocabulary covering agricultural areas with 32, 000 concepts. Ontologies of specific crops were also studied. Amarger et al. (2014) created a wheat ontology. Haverkort and Top (2011) constructed a potato ontology, with the purpose to support automated decision support systems and data exchanging. Thunkijjanukij (2009) proposed an ontology for domain knowledge of rice production.

Considering the use of ontology makes the comprehensive and detailed formalization of any subject domain possible, Abayomi-Alli et al. (2021) offered a method to acquire, store, and obtain organic farming-based information available for software developers who may wish to develop applications for farmers. Because the existing ontologies in the agricultural domain may lack information about seeds, fertilizers, pesticides, various Govt. Schemes, weather, and soil recommendations along with crop management techniques, Jatwani et al. (2018) presented a method to generate ontology of agriculture domain in the uniform structured data (RDF/OWL) format. In particular, they focused on RDF format for publishing and linking data for information sharing so that farmers are provided relevant and contextual information timely and accurately.

Specially regarding citrus planting, Changhua and Chunqiao (2018) created a citrus pest management ontology, and provided a user-friendly interface system to benefit agricultural experts uploading or revising it. Wang et al. (2015) produced three citrus decision services including fertilization, nutrient imbalance, and irrigation/drainage on the basis of semantic knowledge, for serving citrus planting farmers in Chongqing, China. Thanks to such services, the farmers can retrieve the expected services by accessing the website (i.e. it offers the citrus decision services), to direct farming activities. But their released ontology has very limited knowledge about types and quantities of fertilizers, and does not support semantic reasoning for learning new knowledge.

Ontology-based Agricultural Systems: Agricultural systems are knowledge-intensive IT systems that require rich domain knowledge for providing complex and reliable agricultural services and decision support. A number of ontology-based agricultural systems have been proposed (Wang et al., 2015; Beck et al., 2009). Beck et al. (2009) developed an ontology-based environment for simulating citrus and sugarcane nutrition management. Wang et al. (2015) proposed the citrus query system, through which users can query citrus fertilization amount for different growth stages, citrus diseases by inputting symptoms and moisture condition of orchard. The core of the query system is a small scale RDF ontology. Goumopoulos et al. (2009) proposed an ontology-driven architecture for precision agriculture applications. The PLANTS ontology models the knowledge about plant, sensors, actuators and other domain concepts. Fu et al. (2019) constructed an ontology library that is composed of ontology metadata information base, ontology concept library and ontology concept relationship set, for the purpose of helping users to retrieve relevant information in agricultural production.

After surveying existing semantic resources and their construction methods, data interchange standards in the application of semantic web technologies for agricultural problems, Drury et al. (2019) concluded that "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". On the other side, automation systems without ontologies have limited capabilities to conduct complex agricultural activities such as decision making due to the lack of domain knowledge, since it requires providing complex and reliable agricultural services requires rich and high-quality knowledge.

From the above discussions, we observed that most agricultural ontologies were at the vocabulary level with limited inference capabilities. Thus, agricultural systems based on these ontologies cannot provide mature management services for citrus or other crops. Our work fills this gap by presenting a rich and high-quality citrus ontology: CFO with inference capabilities realizing by OWL and BN. Proper types of fertilizers for citrus orchards with different soil conditions and different nutrition status can be obtained by inference from CFO. In addition, combing automation and semantic technologies can benefit crop production management by saving labors and costs and at the same time ensuring complex decision support. That is, it is a challenging task to seamlessly integrate the ontology framework with automation control systems. Such factors drive us designing a citrus fertilization ontology to direct fertilization in citrus planting.

3. SYSTEM DESIGN AND CITRUS FERTILIZATION ONTOLOGY

3.1 Overview of the System

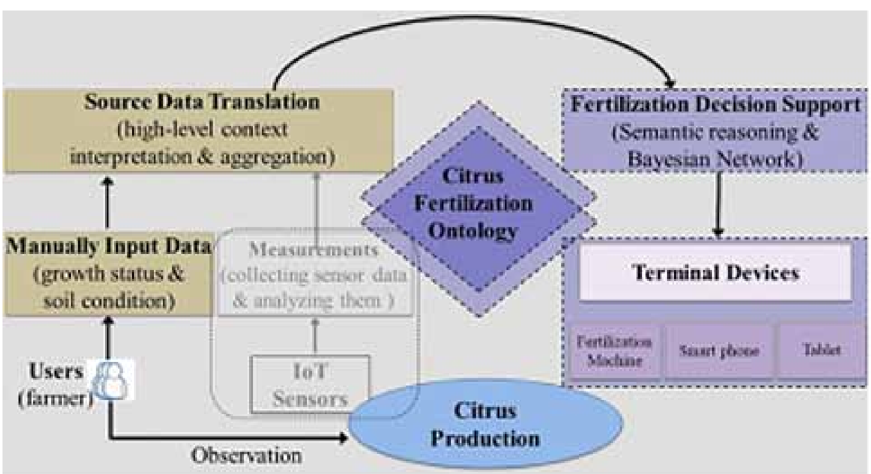
Figure 1 shows a high level functional overview of the proposed ontology-based fertilization system. The CFO models and integrates the domain knowledge related to citrus fertilizers and fertilization. The input data of the system include growth status of citrus trees located in different orchards. In addition, properties of the orchards such as soil conditions are also inputs of the system. Our final goal of implementation is to collect some of input data such as soil conditions using Internet of Things (IoT) sensors, as shown in the grey and dotted rectangle in the figure. Currently, the deployment of IoT sensors is under construction and all the input data are collected manually. That is to say, we need manually feeding the system with the features of citrus plants, for achieving a proper fertilization recommendation.

The fertilization decision support system relies on the CFO to generate fertilization strategies for the users. Specifically, the CFO can be used to query and reason the proper types of fertilizers for different citrus orchards. Furthermore, BN is used to classify citrus trees into different states according to their input symptoms. Fertilization quantities of proper fertilizers can be calculated based on the states. The fertilization strategies obtained by the fertilization decision support system can be accessed through various end devices such as smart phones and Tablet computers. In this paper, we demonstrate how to operate a fertilization machine based on the fertilization decision support system.

3.2 The Citrus Fertilization Ontology

This section discusses the design of the citrus fertilization ontology, including building the ontology in Section 3.2.1 and the BN extension to the ontology in Section 3.2.2.

Figure 1. Architecture of the ontology-based fertilization system



3.2.1 Modeling Citrus Fertilizer Knowledge

We have modeled the knowledge about citrus fertilization to build the ontology from scratch by basically referring to (Allemang & Hendler, 2011), which suggests the modeling procedure of identifying classes and instances first, and then properties that relate instances.

In the current version of ontology (i.e. ver. 2.9.10), 37 types of fertilizers are included in the citrus fertilization ontology. Figure 2 shows the major classes of the ontology (c.f. Appendix A shows more information about the classes of the ontology). As seen, *CitrusFertilizer* is a web ontology language (OWL) class and its members are fertilizers defined as instances such as Borax and CalciumNitrate. More specifically, the main properties associated with CitrusFertilizer are acidBase, fertilizerType, fertilizationMethod, nitrogenRatio, phosphateRatio, potassiumRatio, and farmerInstruction. In addition, the ontology also consists of certain Restriction classes, which are defined by referring to these main properties. For example, AcidFertilizer and AlkalineFertilizer are defined as restriction classes by the property acidBase (Acid or Alkaline).

To illustrate the capabilities of our proposed ontology, we take four citrus orchards as examples. Each orchard has its own conditions related to tree-age, yield of last year, soil, terrain, and typical symptoms of citrus trees, as shown in Table 1. In order to obtain the proper fertilizers for orchards, we define two restriction classes for each orchard, Class *A* and Class *B*. Figure 3 presents the definitions of Class *A* and Class *B* for Od1. We first create two restriction classes for specifying that alkaline fertilizers and chloride fertilizers should not be used (Figures 3(a) and 3(b)) according to the soil

Figure 2. Major classes and properties defined for citrus fertilizers

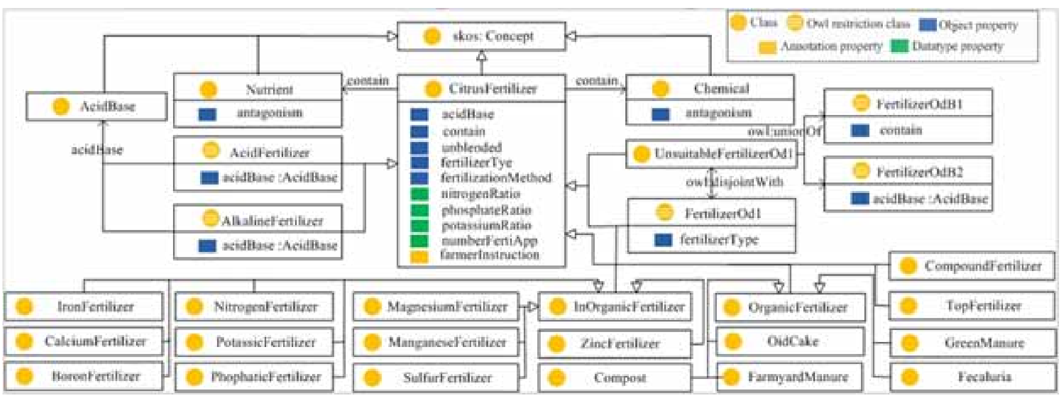


Table 1. Four target citrus orchards in Chongqing

Orchard	Tree age	Last-year yield (kg/hm^2)	Terrain	Soil property	Symptom
Od1	8	30, 000	Hill top	Light yellow, sandy and alkaline	Yellow leaf & low fruit-setting
Od2	8	17, 250	Hill side	Red yellow, clay and acid	Normal
Od3	7	24, 450	Hill top	Red, clay and acid	Few flowers & thick peel
Od4	5	22, 050	Hill valley	Purple, clay and neutral	Yellow leaf & shoot Shriveling

Figure 3. Definitions of Class A and B for the orchard Od1

```
:FertilizerOd1B1
    a owl:Class ;
     rdfs:label "unsuitable to Od1: chloride "@en ;
     rdfs:subClassof :CitrusFertilizer ;
     owl:equivalentClass
          [ a owl:Restriction ;
             owl:hasValue :Chloride ;
            owl:onProperty :contain
          ].
```

(a) Part unsuitable fertilizers for *Od1* (I. chloric)

```
:FertilizerOd1B2
    a owl:Class ;
     rdfs:label "unsuitable to Od1: alkaline"@en ;
       rdfs:subClassOf :CitrusFertilizer ;
      owl:equivalentClass
        [ a owl:Restriction ;
             owl:hasValue :Alkaline;
         owl:onProperty :acidBase
        ] .
```

(b) Part unsuitable fertilizers II for *Od1* (II. alkaline)

```
:UnsuitableFertilizerOd1
   a owl:Class ;
   rdfs:label "unsuitable to Od1: all "@en ;
   rdfs:subClassOf  :CitrusFertilizer ;
   owl:unionOf (:FertilizerOd1B1 :FertilizerOd1B2).
```

(c) Unsuitable fertilizers for *Od1(i.e. Class B)*

```
:FertilizerOd1
      a owl:Class ;
      rdfs:label "suitable fertilizers for Od 1"@en ;
      rdfs:subClassOf :CitrusFertilizer ;
      owl:equivalentClass
        [  a owl:Restriction ;
         owl:hasValue :OrganicFertilizer ;
           owl:onProperty :fertilizerType
        ] .
```

(d) Suitable fertilizers for *Od1 (i.e. Class A)*

conditions of Od 1. Then, the union of the two classes defines the unsuitable fertilizers (i.e. Class *B*), as described in Figure 3(c). UnsuitableFertilizerOd1 is Class *B* for Od1 and it contains eight kinds of fertilizers (Figure 4 (a)). Organic fertilizers are advised because of the alkaline soil of Od1, and Figure 3(d) defines the corresponding restriction class, which is Class *A*. FertilizerOd1 is Class *A* for Od1 and it also contains eight fertilizers (Figure 4 (b)).

Let *F* be the set of fertilizers defined in the CFO and *F* has 37 members currently. Then, the set of fertilizers $F-B$, where "$-$" denotes the set difference operation, includes the fertilizers that can be applied to the orchard. Since the functionality of set difference is not supported by the OWL inference engine of TBC, we obtain $F-B$ by the SPARQL query as shown in Figure 5. Thus, 29 types of fertilizers can be used in Od1. In addition, the fertilizers contained in Class *A* should be given priority when selecting fertilization.

Figure 4. (a) Fertilizers in Class B for Orchard Od1 (Screenshot from TBC); (b) Fertilizers in Class A for the orchard Od1 (Screenshot from TBC)

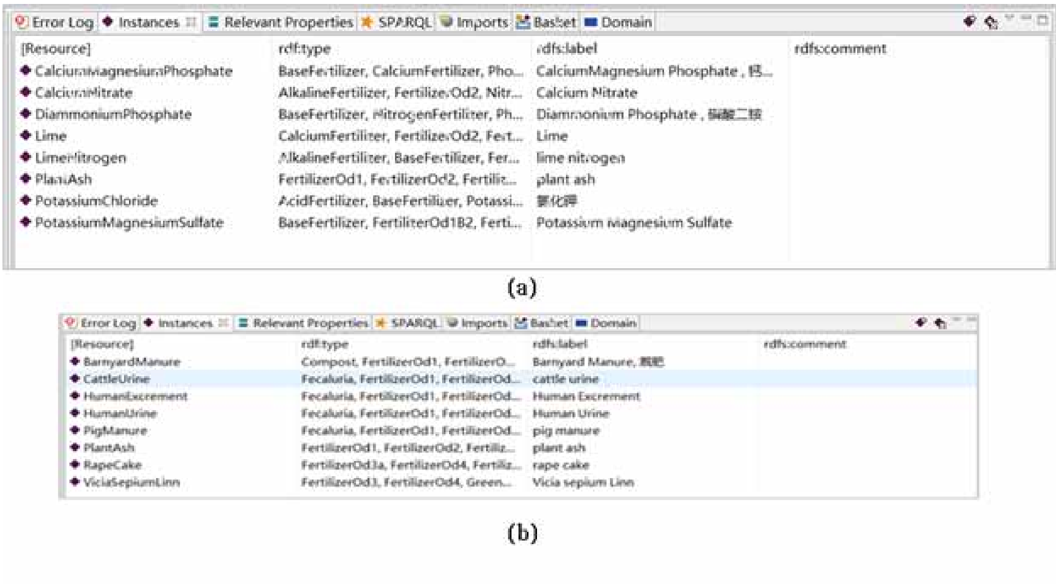
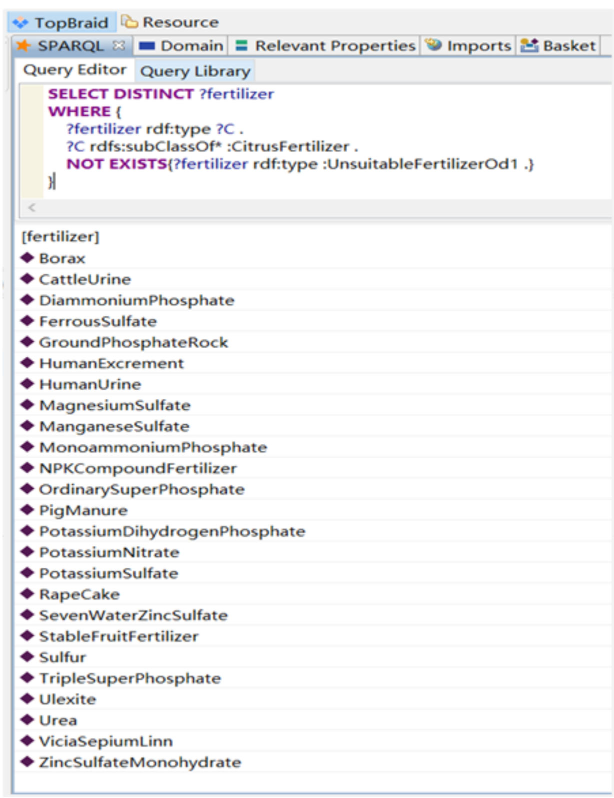


Figure 5. Fertilizers recommended for Od1 (F−B) by SPARQL query (Screenshot from TBC)



The advantage of our fertilizer model is that the proper fertilizers for the orchard Od1 can be obtained by the reasoning capabilities of OWL given the set of citrus fertilizers. Moreover, when the set of fertilizers change over time due to various reasons, e.g., some fertilizers fail to meet the country's latest standards and need to be removed, and new fertilizers are produced, the suitable fertilizers for Od1 can be updated automatically without manually operations.

3.2.2 Bayesian Network Extension to the CFO

The CFO is able to provide proper types of fertilizers for citrus orchards based on their specific conditions. But, in addition to the types of fertilizers, we also need to determine the accurate quantities of fertilizers applied at each growth stage of citrus trees. Generally speaking, the yearly fertilization amount for adult trees is calculated based on the yield of last year (Wang et al., 2015). However, citrus trees usually have NRDs, e.g., lack of nitrogen or excess of potassium (Zeng et al., 2013). Therefore, fertilization management for citrus production should consider NRDs during fertilization application at each growth stage of citrus trees.

In practice, domain experts judge a specific NRD by observing multiple (normally more than two) symptoms a citrus tree exhibits. Some symptoms of citrus are common to different NRDs. In most cases, it is impossible to determine the cause from the observation of a single symptom. For example, the symptom: *low fruit-setting* may be caused by nitrogen excess or deficiency.

Different to the existing disease diagnosis approaches for citrus, our method is to make a decision about NRDs with a single or two symptoms by reasoning with BN. Our method is to incorporate the BN into the CFO. The reason for choosing BN is that the inference involves probability. After analyzing the statistical data on citrus fertilization, we have obtained the prior probability distribution, with respect to different fertilization state on the fertilizers of nitrogen, phosphorus, and potassium, as demonstrated in Appendix B Table 8.

We consider six types of NRDs, i.e., nitrogen deficiency (ND) or excess (NE), phosphorus deficiency (PD) or excess (PE), and potassium deficiency (KD) or excess (KE). Figure 6 shows the relations between symptoms and the six types of NRDs. Table 2 summarizes the citrus symptoms (referred to as *features*) related to NRDs (referred to as *disease classes*). This portion of knowledge is modeled as corresponding ontology classes, instances, and properties in the CFO.

Figure 6. The consequence graph of citrus nutrition related diseases. Note: Numbers in the circles are the symptoms of citrus listed in Table 2. Optimum states of nitrogen, potassium, and phosphorus are omitted in this graph.

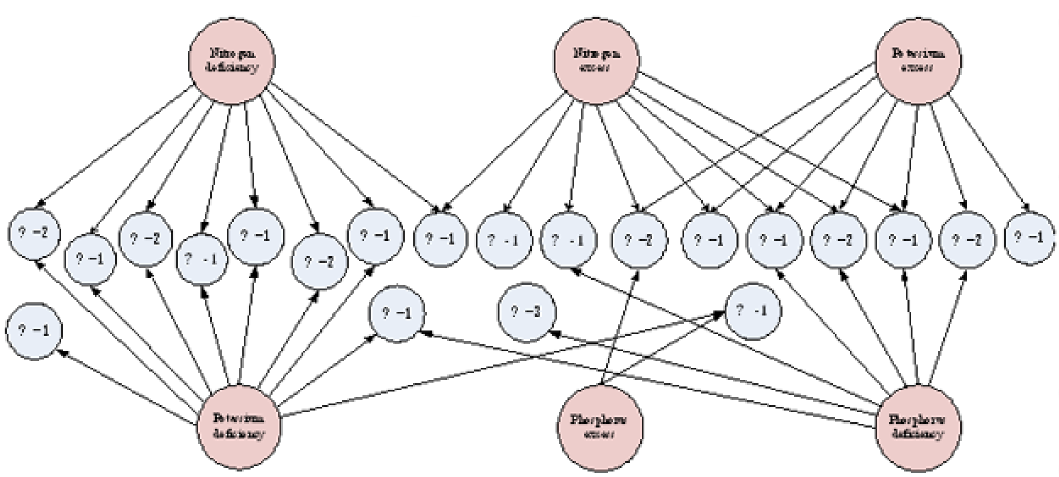


Table 2. Features related to NRDs and their values

Features of Citrus		Value
Leaf symptom	1. Color of Leaves	1. Yellow 2. Normal 3. Bronze
	2. Fallen Leaves	1. Yes 2. No
	3. Burned Leaf Margin	1. Yes 2. No
Fruit symptom	4. Thickness of Peel	1. Thick 2. Thin 3. Normal
	5. Size of Fruit	1. Large 2. Small 3. Normal
	6. Level of Juice Content	1. High 2. Low 3. Normal
	7. Fruit Coloring Time	1. Early 2. Late 3. Normal
	8. Fruit Acidity	1. High 2. Low 3. Normal
	9. Level of Fruit Setting	1. Low 2. Normal
	10. Smoothness of Fruit Peel	1. Smooth 2. Coarse
	11. Fruit Shrinkage	1. Yes 2. No
Shoot symptom	12. Shoot Shriveling	1. Yes 2. No
	13. Thickness of Shoot	1. Thick 2. Normal
Flower symptom	14. Quantity of Flowers	1. Few 2. Normal

A feature instance is defined as a vector $\boldsymbol{X}=(x_1, \ldots, x_n)$. $Y=\{c_1,\ldots, c_N\}$ is the set of disease class labels, i.e., ND, NE, PD, PE, KD, KE, NO (nitrogen optimum), PO (phosphorus optimum), and KO (potassium optimum). We use equation (1) to classify a given feature instance into a disease class:

$$P\left(Y = c_k \mid X = x\right) = \frac{P\left(Y = c_k\right)\prod_j P\left(X^{(j)} = x^{(j)} \mid Y = c_k\right)}{\sum_k P\left(Y = c_k\right)\prod_j P\left(X^{(j)} = x^{(j)} \mid Y = c_k\right)} \tag{1}$$

The priori probability distribution of $P(c_k)$ (k=1,.., N) and the conditional probability $P(X^{(j)}=x^{(j)}|Y=c_k)$ (j=1,…, M, k=1, …, N), where M is 34 and N is 9, are also stored in the CFO (c.f. Appendix B Tables 8 and 9). Since the value of $\sum_k P\left(Y = c_k\right)\prod_j P\left(X^{(j)} = x^{(j)} \mid Y = c_k\right)$ in (1) is a constant and the values of the feature variables are fixed, we simplify (1) as equation (2):

$$\hat{y} = \underset{c_k}{\operatorname{argmax}}\, P\left(Y = c_k\right)\prod_{ij} P(X^{(j)} = x^{(j)} \mid Y = c_k) \tag{2}$$

Take Od1 as an example. Od1 has feature values: *yellow leaf* (①-1) and *low fruit-setting* (‰-1) as given in Table 1 and 2. By (2), we obtain that the probability of ND under the condition *yellow leaf* and *low fruit-setting* is 0.58, which is the largest probability compared to other disease classes (c.f. Appendix B for detailed calculation). Therefore, we conclude that citrus trees in Od1 are lack of nitrogen, i.e., ND.

3.3 Citrus Fertilization Management Based on CFO

A fertilization system normally provides the quantities of pure N, P, and K, but fail to recommend specific types of fertilizers that can be used (Wang et al., 2015; Zeng et al., 2013; Li et al., 2020).

Different to existing approaches, our fertilization approach can provide not only the proper types of fertilizers based on the conditions of each orchard but also quantities of these fertilizers as well as farmer instructions for coping with NRDs.

As described in Section 3.2.1, the suitable fertilizers for Od1 can be reasoned by the OWL restriction classes (Figures 3 and 4) and Sparql query (Figure 5). Then, we need to calculate the quantities of the suitable fertilizers applied to Od1 at each growth stage within a year. In general, the yearly fertilization amount for adult trees is subject to the yield of last year and the terrain of an orchard. Equation (3) is the yearly fertilization amount (kg/hm^2) for pure N (Wang et al.,2015), where *Yield* is the yield of last year (kg/hm^2), k_t is the coefficient subject to the terrain (hill top, side, or valley):

$$YearlyQN = k_t \cdot \left(0.01214 \cdot Yield - 64.26\right) \tag{3}$$

From Table 1 we know that *Yield* for Od1 is 30, 000 kg/ hm^2, k_t is set to 1.2 for hill top^2 (Wang et al.,2015). By (3), the quantity of yearly fertilization is 359.93 kg/hm^2. Similar formulae are available for calculating the quantity of pure P and K and thus we can obtain *YearlyQP* and *YearlyQK* for Od1.

There are four growth stages: germination, swelling, stabling, and picking stages, which are the major fertilization periods in a year. Table 3 shows the suggested ratios of fertilization at each growth stage. According to Table 3, we are able to calculate the quantities of pure N (P and K) for each growth stage. For example, the amount of N for the germination stage is 359.93 (kg/hm^2) ×10% ~359.93 (kg/hm^2) ×15%, i.e., 35.99 (kg/hm^2) ~53.99 (kg/hm^2). How to choose the proper ratios from the given range of the ratios is not specified but decided by farmer's experience (Zeng et al., 2013).

Our solution for selecting the proper fertilization ratios is based on the result of possible NRDs classified by the BN. For example, citrus trees in Od1 have two symptoms: *yellow leaf* and *low fruit-setting* and the BN classifies Od1 as ND. Therefore, at each stage of fertilization, we recommend the upper bound of the ratio ranges. For Od1, the fertilization ratios at the four growth stages are 15% (germination stage), 15% (stabling stage), 70% (swelling stage), and 10% (picking stage) respectively. Table 4 summarizes the fertilization ratios for the four growth stages in case of different NRDs suggested by our approach. Compared to Table 3, which suggests ranges of ratios, our approach can recommend the proper fertilization ratios based on the result of possible NRDs classified by the BN. Besides, the knowledge of farmer's instructions (Wang et al., 2016; Zeng et al., 2013) for coping with different NRDs are also stored in the CFO in terms of rdfs:comment and will be provided for the system users during fertilization application.

4. SYSTEM EVALUATION

In our project, we manage the CFO using the semantic database AllegroGraph 6.1. The fertilization application is developed with Java and the Sesame API is used for accessing AllegroGraph. The fertilization system is deployed on a computer with dual-processor Intel® E5800 3.2G Xeon-based CPU having 4 GB RAM. This section will first evaluate the CFO. Then, the functionalities of our fertilization system will be described.

Table 3. Fertilization ratios for the four growth stages

Growth stage	Germination stage	Stabling stage	Swelling stage	Picking stage
Fertilization ratio	10%~15%	10%~15%	60%~70%	10%

Table 4. Yearly fertilization ratios and farmer's instructions for NRDs

NRD	Fertilization ratios for growth stages				Farmer's instruction
	Germination	Stabling	Swelling	Picking	
ND	15%	15%	70%	10%	Foliar spray 0.5% urea once every 5~7 days and apply 2~3 times.
NE	10%	10%	60%	10%	Use proper nitrogen fertilizers, change fertilization method and period, and reduce fertilization amount.
PD	15%	15%	70%	10%	Foliar spray 0.5%~1% calcium superphosphate once every 7~10 days and apply 2~3 times.
PE	10%	10%	60%	10%	Apply phosphate fertilizers correctly. Increase the amount of nitrogen and potassium fertilizers.
KD	15%	15%	70%	10%	Foliar spray 0.5%~1% potassium sulphate once every 5~7 days and apply 2~3 times.
KE	10%	10%	60%	10%	Stop using chemical potassium fertilizers and increase the use of proper nitrogen and phosphate fertilizers.
NO/PO/KO	12.5%	12.5%	65%	10%	N/A

4.1 Ontology Evaluation

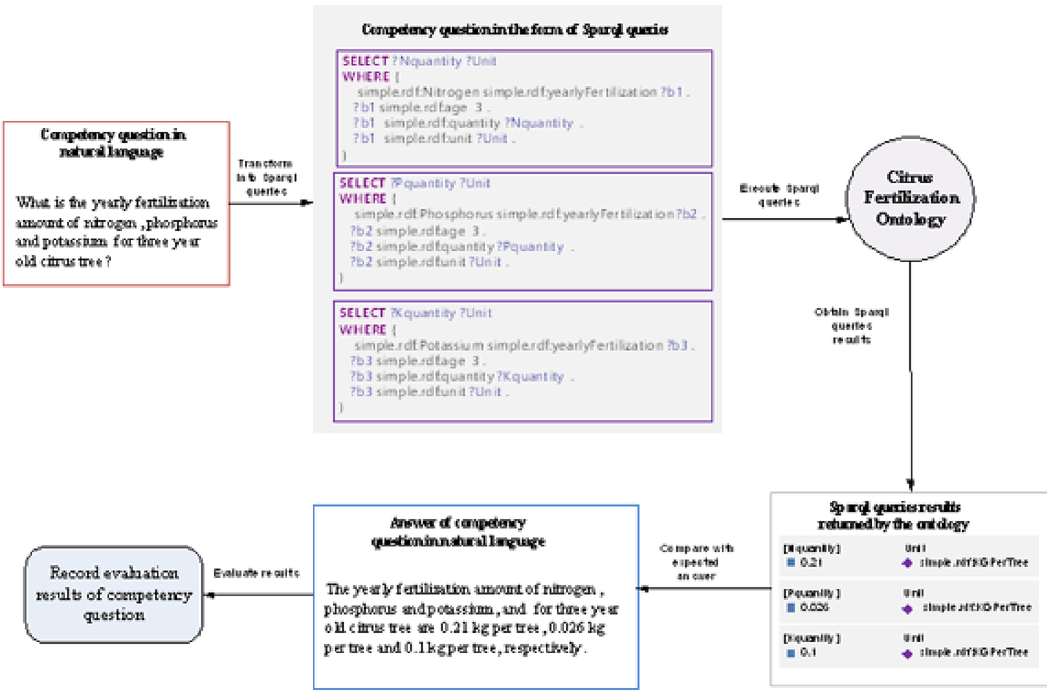
4.1.1 Competency Evaluation

The CFO models citrus fertilization knowledge which is essential for the functionalities of the proposed fertilization system. Before we carry out functional evaluation of the system, we need to validate the correctness of the fertilization knowledge modeled by the CFO. The CFO contains 103 classes, 800 instances, and 34 properties. These ontology entities are described by 3056 RDF triples. How to efficiently validate large ontologies is a challenging task (Vrandečić, 2004). In the literature, a number of methods were proposed to support ontology validation with different goals and requirements (Santos et al., 2019; Vrandečić, 2004; Alaoui & Bahaj, 2019). The unique criterion for ontology validation is *competency*, which is measured by competency questions (CQs) (Allemang et al. 2011). Since the ultimate goal of the CFO is to support citrus fertilization management, we applied CQ evaluation to the CFO. Figure 7 outlines the CQ evaluation procedure.

First, we designed CQs in the form of natural language. Figure 7 shows an example CQ: *What is the yearly fertilization amount of nitrogen, phosphorus, and potassium for three year old citrus trees?* The CQ was then transformed into Sparql queries manually and executed in the TBC. As shown in Figure 7, the example CQ was transformed into three Sparql queries. The returned query results from the ontology were then compared with the expected answers in the form of natural language. Figure 7 displays the three returned sparql queries, which are compared with the expected answer: "*The yearly fertilization amount of nitrogen, phosphorus, and potassium for three year old citrus trees are 0.21 kg per tree, 0.026 kg per tree, and 0.1 kg per tree respectively.*" The final step is to record the evaluation results.

The design of CQs and their expected answers were validated by the domain expert[3]. In total, we designed 90 CQs, which cover general knowledge of citrus fertilizers and fertilizer applications. The accuracy of the CQ evaluation for the 90 CQs is 89%, i.e., the CFO failed to answer 10 CQs. The main cause of the failed 10 CQs is the deficiency or incompleteness of a specific portion of knowledge related to citrus fertilizers and fertilization.

Figure 7. CQ evaluation procedure



4.1.2 Comparison With Other Citrus Ontologies

This section compares our ontology of CFO with the two most relevant citrus ontologies in the existing studies (Beck et al., 2009; Wang el al., 2015), and Table 5 shows the results. As seen, it reports the results from 4 aspects of ontology: scale of the ontology, level of semantic richness, inference capability, and knowledge coverage (Vrandečić, 2004).

The feature of *scale of ontology* provides the metrics about the scale of an ontology. CFO has 103 domain classes compared to 7 (Beck et al., 2009) and 22 (Wang et al., 2016). Beck et al. (2009)

Table 5. Comparison results of citrus ontologies

Citrus ontology	Scale of the ontology			Level of semantic richness	Inference capability	Knowledge coverage
	No. of domain classes	No. of instances	No. of domain properties			
CFO	103	800	34	proper ontology	type propagation + OWL restriction + BN	citrus fertilizers, fertilization strategies, and NRDs
Beck et al. (2009)	7	1200	3	formal taxonomy	type propagation	soil, watering, and nutrients in the form of equations
Wang et al. (2015)	22	90	36	formal taxonomy	type propagation	general fertilization methods, nutrient imbalance, and watering

defined 1200 instances, which are equations and symbols related to soil, watering and nutrients relations. Differently, CFO and Wang et al. (2016) modeled domain knowledge described in natural language, rather than pure equations. Beck et al. (2009) defined the smallest set of domain properties compared to the other two ontologies.

The feature of *level of semantic richness* refers to the spectrum of semantic richness for ontologies (Vrandečić, 2004). Ontologies can range from simple and inexpressive to highly complex and precise: catalogs, glossaries, thesauri, formal taxonomies, and proper ontologies. The more expressive an ontology is, the more intelligent and complicated the applications it can support. A catalog-type ontology refers to a list of the entities IDs. A glossary-type ontology refers to a set of definitions of terms. A thesaurus-type ontology includes a set of terms with a number of pre-deðned relations between them. A formal-taxonomy-type ontology refers to a set of concepts with subsumption relationships. Finally, a proper ontology is an ontology with all possible axioms, such as OWL restrictions. By these definitions, CFO is a type of proper ontology, while the other two ontologies are taxonomy type.

The feature of *inference capability* describes what kind inference can an ontology support. CFO supports reasoning with rdfs:subClassOf and OWL:restrictions. The inference using rdfs:subClassOf is called type propagation (Alaoui & Bahaj,, 2019). In addition, we extended the ontology with BN, which can infer citrus trees into specific type of NRDs. The ontologies in (Beck et al., 2009) and (Wang et al., 2016) only support type propagation.

The feature of *knowledge coverage* refers to what portion of domain knowledge an ontology models. CFO focuses on modeling citrus fertilization knowledge with specific types of fertilizers and NRDs. The goal is to recommend precise fertilization for citrus trees in different nutrient conditions. The ontology created by Wang et al. (2016) has similar knowledge coverage, but fails to model the different types of fertilizers and the fertilization–related information (e.g., the nutrient ratios in different type of fertilizer and the acid-base properties). It covers general fertilization knowledge without specific fertilizer types and quantities. Beck et al. (2009) has a different focus on modeling domain knowledge: equations about soil, water, and nutrients.

In summary, compared to the existing citrus ontologies, the newly created CFO ontology achieves better performance with respect to three aspects of scale, level of semantic richness, and inference capability, though it has a different focus on knowledge coverage.

4.2 System Functional Evaluation

The objectives of system functional evaluation are: (1) validating the accuracy of the quantities of pure N, P, and K at the four growth stages for the four example citrus orchards, and (2) evaluating the suitability of the recommended fertilizers for the four sample citrus orchards. Table 6 presents the quantities of pure N, P, and K and the suitable fertilizers advised by our system for the four citrus orchards at the four growth stages.

4.2.1 Evaluation of Fertilization Accuracy

We compared the quantities of N, P, and K with the experience-based method. The experience-based method refers to the fertilization decisions made by local farmers[4]. Figure 8 illustrates the evaluation results, where each sub figure corresponds to the fertilization of the four orchards. In each of the sub figure, the horizontal axis is the growth stage, and the vertical axis is the ratio of *recommended* fertilization quantity versus the *expected* fertilization quantity. Here, the expected fertilization quantity is regarded as a benchmark, which was obtained from the domain experts[5]. The recommended fertilization quantity refers to the value advised by our system (as shown in Table 6) or the value of the experienced-based method.

As shown in the Fig ure8, the fertilization quantities for pure N, P, and K advised by our system are completely consistent to the expectation. On the contrary, the experience-based method had inadequate fertilization (e.g., Figure 8(a)) or excessive fertilization (e.g., Figure 8 (b)).

Table 6. Fertilization recommendation based on the CFO

Orchard	Germination/Stabling stage		Swelling stage		Picking stage	
	Quantities of N/P/K	Quantities of suitable fertilizers	Quantities of N/P/K	Quantities of suitable fertilizers	Quantities of N/P/K	Quantities of suitable fertilizers
Od1	N (54)	Urea (59) & HE (2700)	N (252)	Urea (274) & rape cake (2739)	N (36)	HE (2159) & barnyard manure (2999)
	P (36)	CS (225)	P (187)	CTS (407)	P (29)	GPR (144)
	K (45)	PS (90)	K (234)	PS (469)	K (36)	PS (72)
Od2	N (18)	Urea (39)	N (94)	Lime nitrogen (225) & urea (103)	N (14.52)	HE (1452)
	P (13)	CMP (84)	P (70)	CMP (439)	P (10.79)	GPR (53.95) & plant ash (450)
	K (17)	PMS (80)	K (91)	PMS (414)	K (14.00)	PMS (63.64)
Od3	N (28)	Lime nitrogen (67) & HE (1396)	N (167)	Urea (218) & HE (6698)	N (28)	Barnyard manure (2907) & urea (30)
	P (27)	CMP (171)	P (142)	CMP (890)	P (22)	CMP (137) & lime (2250)
	K (35)	PS (69)	K (180)	PS (360)	K (28)	PS (55)
Od4	N (20)	Lime nitrogen (48) & rape cake (221)	N (106)	Urea (138) & rape cake (920)	N (16)	Barnyard manure (1695) & lime nitrogen (39)
	P (16)	GPR (79)	P (82)	GPR (410)	P (13)	CMP (79)
	K (24)	PS (48)	K (112)	PS (224)	K (16)	PMS (73)

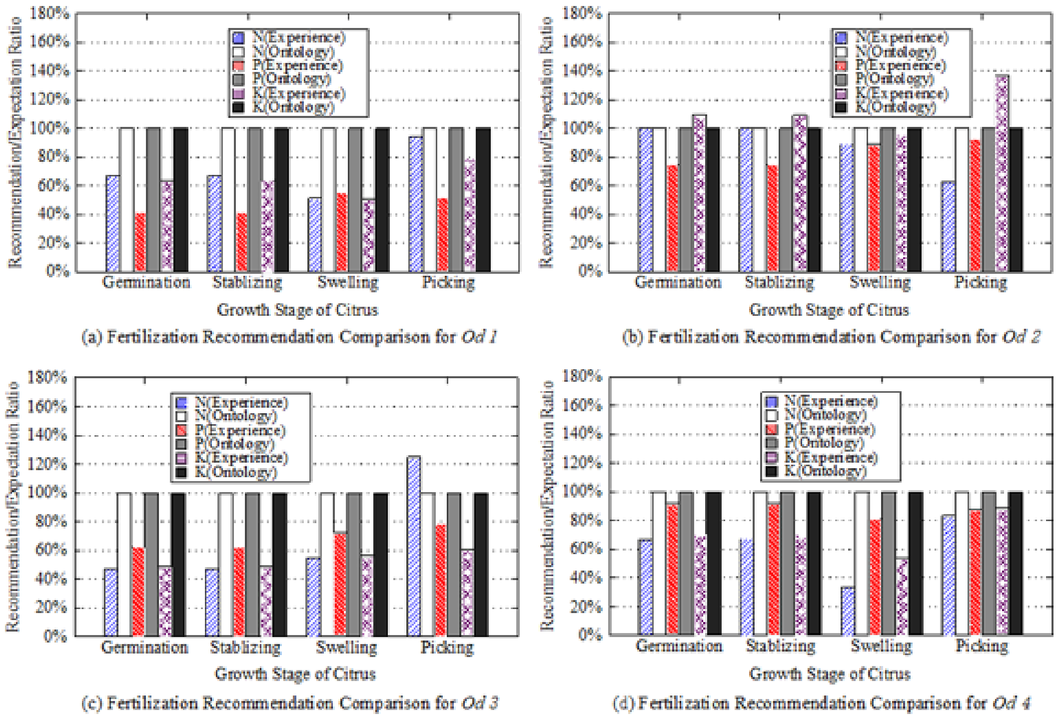
Note: (1) the unit is kg/hm^2. (2) Since the fertilization quantities at the germination stage equal those at the stabling stages, we merge the two stages into one column. (3) Abbreviations: **HE** for Human Excrement, **CS** for Calcium Superphosphate, **PS** for Potassium Sulfate, **CTS** for Calcium Triple Superphosphate, **GPR** for Ground Phosphate Rock, **CMP** for Calcium Magnesium Phosphate, **PMS** for Potassium Magnesium Sulfate.

4.2.2 Evaluation of Fertilizer Recommendation

Table 6 shows the N, P, and K fertilizers and their quantities at each growth stage for the four orchards advised by our system. By querying the CFO, we can obtain the nutrition percentages contained in each type of fertilizer, and thus calculate the quantities of fertilizers. For example, potassium sulfate contains 50% of potassium. Given the value of pure K: 234.47 (kg/hm^2), we can obtain that the quantity of potassium sulfate is 468.94 (kg/hm^2). Since we have validated the correctness of the ontology and the quantities of pure N, P, and K, we did not evaluate the quantities of the suitable fertilizers anymore.

In this section, we evaluated the suitability of advised types of fertilizers only. In other words, the objective of this evaluation is to judge if the recommended fertilizers are proper for each orchards. We provided the two domain experts with the information: (i) the conditions of the orchards as shown in Table 1, and (ii) the recommended fertilizers for the four orchards at different growth stages as shown in Table 6. During the evaluation process, the experts judged independently the suitability of the recommended fertilizers. The experts can decide if a fertilizer is “suitable”, “unsuitable”, and “neutral”. In the result, we regard a fertilizer as unsuitable if any of the experts think it is “unsuitable”. The evaluation result is 97.1% correct, i.e., the advised fertilizers contain no unsuitable fertilizers for the orchards concerning their specific conditions.

Figure 8. Comparison of fertilization recommendations for the four orchards at the four growth stages (Note that "Experience" refers to the experience-based method, and "Ontology" refers to our ontology-based system)



4.2.3 Comparison With Other Systems Based on Citrus Ontologies

This section makes a comparison between our systems and the systems developed in existing work of semantic-based citrus planting, from the aspects of the development environment and system functions.

Table 7 summarizes the development environment and system function of our system together with the other ontology-based citrus planting systems. Both our system and the system in (Wang et al. 2016) were developed using AllegroGraph database and Java. Differently, Beck et al. (2009) used Lyra ontology management system, which can create, manage ontologies, and simulate based on the defined ontological model.

Table 7. Comparison results of citrus systems

Ontology-based system	Development environment	System function
CFO-base fertilization system	AllegroGraph+Java+fertilization machine	A fertilization automation system which can recommend yearly fertilization quantities and proper fertilizers according to NRDs and soil properties.
Beck et al. (2009)	Lyra ontology management system	A simulation environment for citrus trees, which can schedule irrigation plans and provide daily reports.
Wang et al. (2016)	AllegroGraph+Java	An android-based mobile application, which can query citrus diseases by symptoms, recommend yearly fertilization amounts, and monitor watering conditions.

Note that both our system and the system proposed by Wang et al. (2015) focused on fertilization management. We used an automatic fertilization machine, made by the Wuhan Zoor Water Saving Irrigation Company[6] as the terminal device. This small-scale machine can trigger fertilization when it receives a command about fertilizer types and quantities. Since the fertilization machine has three cans for pre-loading three types of fertilizers, we use this machine to apply chemical nitrogen, phosphorus, and potassium fertilizers respectively. The system proposed by Wang et al. (2015) is an android-based mobile application, which supports citrus disease diagnosis by inputting symptoms, acquiring yearly fertilization quantities of pure N, P, and K (but not proper fertilizers), and monitoring soil watering condition. Differently, Beck et al. (2009) developed a simulation tool for citrus trees, which can schedule irrigation and provide daily reports.

In summary, our ontology-based system is able to provide different functions, in contrast to the existing systems. More specifically, the accurate fertilization recommendation for fertilization quantities and specific fertilizers as well as the application using an automation machine is not addressed in the existing systems of citrus planting.

4.3 Prototype of Fertilization Machine

To apply the proposed ontology-based fertilization approach in citrus field management, we take advantage of an automatic fertilization machine, which is made by the Wuhan Zoor Water Saving Irrigation Company[7] as the terminal device. This small-scale machine can trigger fertilization when it receives a command about fertilizer types and quantities. Since the fertilization machine has only three cans for pre-loading three types of fertilizers, we use this machine to apply chemical nitrogen, phosphorus, and potassium fertilizers respectively. Even though our ontology based fertilization approach can provide proper fertilizers rather than chemical fertilizers, the fertilization machine can only apply three types of fertilizers in the operation. We shall consider more advanced terminal devices for the future work.

5. CONCLUSION

In this paper, we proposed an ontology-based fertilization system for citrus fertilization management. The core of the system is the CFO, which models the knowledge related to citrus fertilizer and fertilization. We discussed how the CFO extended with BN can be used to generate fertilization strategies for citrus orchards with different conditions. The current version of the CFO contains 103 classes, 34 properties, 800 instances, which are defined by 3056 RDF triples. We evaluated the CFO with 90 CQs that cover the general knowledge of citrus fertilization. The CFO achieved 89% accuracy for the CQ evaluation.

We also validated the functions of the proposed system by comparing the advised quantities of pure N, P, and K to the experience-based method for the four example citrus orchards. The results show that our approach is 97.1% consistent to the benchmark values and performs better than the experience-based method. Furthermore, we evaluated the suitability of the recommended fertilizers in an automatic fertilization machine. In brief, our work provides a feasible application for realizing intelligent citrus management system and can be applied to other crop management.

The current implementation of citrus fertilization ontology mainly targets at citrus planting in mountainous region of Chongqing, so that it has been verified in the citrus orchards in Chongqing. That is to say, it may not work for the citrus orchards having varied geographic features. To address this issue, we are planning to extend the CFO for more knowledge such as citrus varieties and their production management in the future. In addition, our current implementation of system requires the planting information collected by citrus farmers to trigger the ontology yielding an fertilization recommendation, even though building a fully automatic fertilization system with IoT sensors is the ultimate goal. Then, applying our well-constructed ontology-based system in commercial IoT platforms will be another direction of future work.

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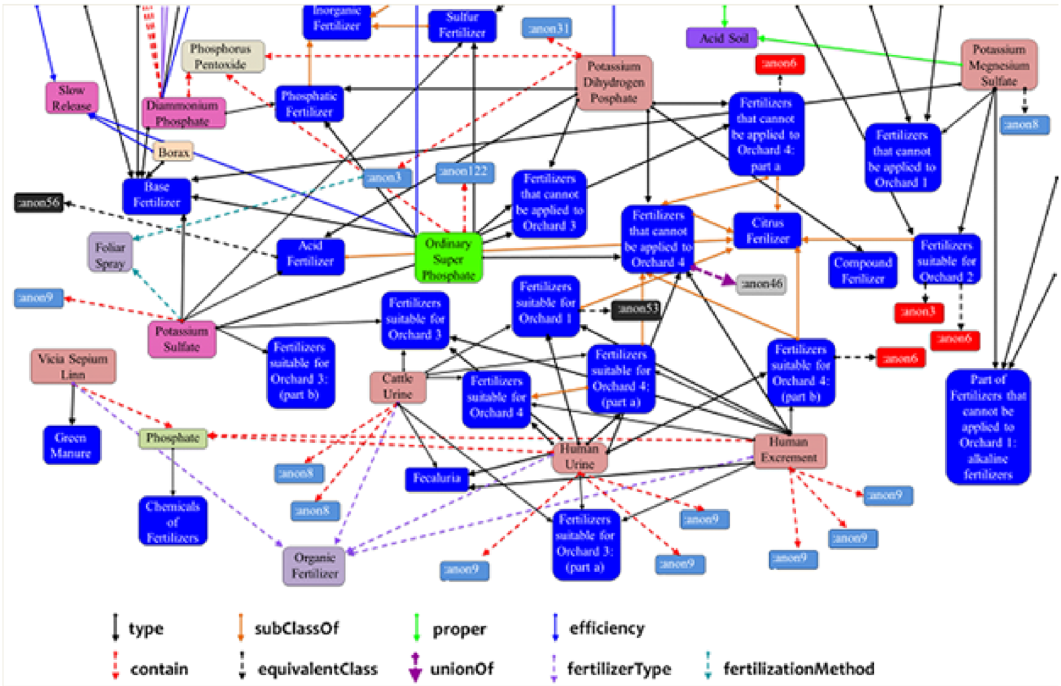
ENDNOTES

1. http://aims.fao.org/vest-registry/vocabularies/agrovoc-multilingual-agricultural-thesaurus
2. Since Chongqing is a mountainous region, fertilization application needs to consider the terrain of orchards.
3. Two domain experts were consulted for the ontology competency evaluation.
4. We interviewed two local farmers working at citrus orchards in Zhongxian, Chongqing. For every values offered by the farmers, we took the average of them.
5. Two domain experts were consulted for the citrus fertilization. For every values offered by the experts, we took the average of them.
6. Automatic fertilization machine. http://www.zoor.com.cn/CaseStd_538.html
7. Automatic fertilization machine. http://www.zoor.com.cn/products-detail.asp?cpid=160

APPENDIX A: ADDITIONAL FIGURES

Figure 9.



APPENDIX B: PRIOR PROBABILITY DISTRIBUTION AND CONDITIONAL PROBABILITY DISTRIBUTION FOR THE NAÏVE BAYES NETWORK

For the purpose of identifying the situations of fertilizer deficiency or excess in citrus orchards by analyzing the symptoms of citrus, we have incorporated the Naïve Bayes classifier into the CFO.

After analyzing the statistical data on citrus fertilization, we have obtained the prior probability distribution, with respect to different fertilization state on the fertilizers of nitrogen, phosphorus, and Potassium, as demonstrated in Table 8.

Furthermore, we have computed the conditional probability distribution, by considering the observed features and our fertilization state (Table 8). Table 9 shows the conditional probabilities.

To demonstrate the process of identifying the target class for a given instance of collected values of features in citrus trees when using the Naïve Bayes classifier, we have list the details about the citrus trees in Od1 is lack of the nitrogen nutrient.

The symptoms in Od1: *Yellow leaf and low fruit-setting*, and we represent the symptoms as the vector of X. We then calculate all values by using the following equation (the numerator part of Equation (2) in the paper), when k=1, 2, …9:

$$P\left(Y = c_k\right)\prod_{ij} P\left(X^{(j)} = x^{(j)} \;|Y = c_k\right)$$

1. ND | X = 0.682 * 0.923 * 0.923 = **0.581015578** (ND: Nitrogen Deficiency, X: feature vector)
2. NO | X = 0.251 * 0.032 * 0.024 = 0.000192768 (NO: Nitrogen Optimum)
3. NE | X = 0.067 * 0.141 * 0.654 = 0.006178338 (NE: Nitrogen Excess)
4. PD | X = 0.411 * 0.002 * 0.368 = 0.000302496 (PO: Phosphate Deficiency)
5. PO | X = 0.543 * 0.044 * 0.012 = 0.000286704 (PO: Phosphate Optimum)
6. PE | X = 0.046 * 0.014 * 0.025 = 1.288e-05 (PO: Phosphate Excess)
7. KD | X = 0.285 * 0.712 * 0.347 = 0.07041324 (KO: Potassium Deficiency)
8. KO | X = 0.451 * 0.013 * 0.034 = 0.000199342 (KO: Potassium Optimum)
9. KE | X = 0.264 * 0.103 * 0.282 = 0.007668144 (KO: Potassium Excess)

Table 8. Prior probability distribution of fertilization in citrus trees

Fertilization (N, P, K) state	Prior probability
Nitrogen Deficiency	68.2%
Nitrogen Optimum	25.1%
Nitrogen Excess	6.7%
Phosphate Deficiency	41.1%
Phosphate Optimum	54.3%
Phosphate Excess	4.6%
Potassium Deficiency	28.5%
Potassium Optimum	45.1%
Potassium Excess	26.4%

Table 9. Conditional probability distribution of fertilization in citrus planting (%)

Features and values	Nitrogen			Phosphate			Potassium		
	Defi.	*Opt.*	*Ex.*	*Defi.*	*Opt.*	*Ex.*	*Defi.*	*Opt.*	*Ex.*
①-*1*	92.3	3.2	14.1	0.2	4.4	1.4	71.2	1.3	10.3
①-*2*	3.7	90.9	68.7	2.4	93.5	95.2	18.3	96.6	75.4
①-*3*	4.0	5.9	17.2	97.4	2.1	3.1	10.5	2.1	14.3
②-*1*	3.2	2.1	8.3	95.8	3.9	4.1	96.4	3.5	12.3
②-*2*	96.8	97.9	91.7	4.2	96.1	95.9	3.6	96.5	87.7
③-*1*	7.9	1.3	6.7	2.2	2.3	1.9	3.2	2.1	89.1
③-*2*	92.1	98.7	93.7	97.8	97.7	98.1	96.8	97.9	10.9
④-*1*	18.2	3.5	93.2	66.9	2.1	2.5	4.5	2.4	91.9
④-*2*	65.1	4.0	2.1	4.3	3.6	2.1	89.3	2.1	1.4
④-*3*	16.7	92.5	4.7	28.8	94.3	95.4	6.2	95.5	6.7
⑤-*1*	12.6	1.2	64.3	4.2	3.2	1.1	1.2	3.1	65.3
⑤-*2*	71.2	2.2	14.3	13.2	0.9	0.6	95.5	1.2	9.2
⑤-*3*	16.2	96.6	21.4	82.6	95.9	98.3	3.3	95.7	25.5
⑥-*1*	2.7	0.8	9.2	2.1	1.2	1.4	71.2	1.2	0.9
⑥-*2*	5.1	0.7	4.3	93.2	3.1	3.5	2.1	0.9	93.2
⑥-*3*	92.2	98.5	86.5	4.7	95.7	95.1	26.7	97.9	5.9
⑦-*1*	68.8	0.9	2.3	1.2	0.9	0.4	89.2	1.2	5.6
⑦-*2*	17.4	1.2	89.7	74.2	1.2	1.1	2.3	2.1	71.2
⑦-*3*	13.8	97.9	8.0	24.6	97.9	98.5	8.5	96.7	23.2
⑧-*1*	15.9	1.1	94.2	95.2	2.2	2.1	3.2	0.3	65.5
⑧-*2*	64.6	0.5	1.2	0.5	1.1	1.4	70.3	2.1	8.2
⑧-*3*	19.5	98.4	4.6	4.3	96.7	96.5	26.5	97.6	26.3
⑨-*1*	92.3	2.4	65.4	36.8	1.2	2.5	34.7	3.4	28.2
⑨-*2*	7.7	97.6	34.6	63.2	98.8	97.5	65.3	96.6	71.8
⑩-*1*	72.1	87.4	65.4	65.4	89.1	15.3	87.8	85.2	10.2
⑩-*2*	27.9	12.6	34.6	34.6	10.9	84.7	12.2	14.8	89.8
⑪-*1*	16.8	7.5	16.2	11.4	4.3	93.5	73.2	4.1	8.2
⑪-*2*	83.2	92.5	83.8	88.6	95.7	6.5	26.8	95.9	91.8
⑫-*1*	94.3	1.2	4.5	2.3	3.2	4.1	95.4	2.8	12.4
⑫-*2*	5.7	98.8	95.5	97.7	96.8	95.9	4.6	97.2	87.6
⑬-*1*	15.3	3.0	88.2	5.3	1.2	1.5	18.9	2.2	15.5
⑬-*2*	84.7	97.0	11.8	94.7	98.8	98.5	81.1	97.8	84.5
⑭-*1*	1.2	3.2	91.6	93.2	2.4	3.7	14.2	1.3	13.2
⑭-*2*	98.8	96.8	8.4	6.8	97.6	96.3	85.8	98.7	86.8

Note: *Defi.* indicates deficiency; *Opt.* means optimum; *Ex.* implies excess. The label of ①-*1* represents the condition is the first feature having the first value.

According to Equation (2) shown in the paper, the largest one from the above 9 values, i.e. the first item is our target to be selected. In summary, we can deduce that the features of *Yellow Leaf and Low Fruit Setting* in *Od 1* means the state of *Nitrogen Deficiency*.

Note that the aforementioned 9 values do not mean the probability, and the sum of these values is not 1.0.

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