Towards Secure Semantic Interoperability in Dairy Farming Systems

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***Abstract*—The dairy industry is undergoing a significant transformation driven by digitisation, data proliferation, and the need for sustainable and efficient production methods. Today, farms generate data from various sources, including soil and grass monitoring systems, milking systems, animal monitoring systems, and weather information systems, utilising a range of devices and software applications. To remain profitable, farmers need to manage their farms and cattle to optimise practices while avoiding losses. Despite the availability of data, the diversity and heterogeneity of dairy farm systems pose a critical challenge for ensuring semantic interoperability while maintaining data privacy. Interoperable dairy farm systems have enabled data sharing among stakeholders, enabling access to comprehensive dairy farm records for informed decision-making. However, data sharing raises risks to data privacy and may expose individuals to unauthorised access and misuse of farm information. In this paper, to achieve semantic interoperability, data standards, such as ontologies, are utilised to establish a shared understanding and enable meaningful information exchange between stakeholders. Domain knowledge is derived from data collected by the Irish Cattle Breeding Federation (ICBF) and the Agriculture and Food Development Authority (Teagasc) to develop the ontologies. In addition, the ontology terms align with dairy farm data standards from sources such as AGROVOC and DataLinker. To evaluate domain ontologies, a query-based approach has been used, with domain experts validating the query results. Finally, this paper proposed a security layer to address security and privacy challenges, such as encryption, anonymisation, and access control. By addressing the privacy challenge, farmers' data becomes securely accessible for interoperability, fostering innovation and sustainability in dairy farm systems.**

***Index Terms*—Standard, ontology, semantic, interoperability, dairy farm**

I. Introduction

The dairy industry is generating substantial data daily through the adoption of emerging technologies and digitisation for automation and data recording, highlighting the urgent need to utilise this data to optimise farm processes. The farms include several subsystems, soil and grass monitoring systems, milking systems, sensor devices, animal monitoring devices, and weather information systems [1]. Each of these subsystems operates in isolation, and no shared semantics are associated with data due to the heterogeneity across systems, devices, and the systems used by the stakeholders. Therefore, semantic interoperability has become a critical challenge in dairy farm systems [2]. The development of semantic interoperability in dairy farming solutions support farmers, policymakers, and other stakeholders in obtaining improved answers to questions regarding soil [3]quality measures, fertilisation [4], quality of grass growth, the effects of weather conditions on soil and grass quality, livestock management [5]and quality milk production [6]. To remain profitable, farmers must effectively manage their farms and mitigate risks that could result in significant losses [7].

Data privacy is an inherent challenge in systems interoperability [8] [9] [10]. Generally, several research teams conduct independent research with limited data sharing, in which farmers share data on soil and environmental conditions, grass quality, and animal monitoring. Based on the researcher's feedback, farmers can make timely decisions about managing farm activities, such as when to water the soil, when to cut grass, and how much grass is enough to store for winter. Moreover, government institutions and policymakers require farm data for future planning to fulfil society's food demand and to support a sustainable environment. However, in the context of interoperability, data sharing with other systems can raise trust issues and lead to data misuse by competitors. Moreover, it can create security threats, including intentional threats such as membership inference and attribute inference, as well as unintentional threats such as configuration errors and improper encryption, which can expose farmers' sensitive information [10]. Therefore, there is a need for a secure semantic interoperability system to empower dairy farm management to be more profitable.

Over the past decade, semantic web technologies have become a popular approach to assigning meaning to data through ontologies. Ontologies provide a community-consensus framework for handling heterogeneity and demonstrate their use in achieving semantic interoperability for seamless information exchange across dairy farm systems [11]. Despite the existence of several ontologies in the agricultural domain, including AGROVOC, BioPortal, and AgroPortal, a comprehensive set of suitable ontologies for practical use is still not available due to several limitations, such as semantic ambiguity, a lack of domain-specific concepts, and the complexity of overlapping concepts across different domains [12].

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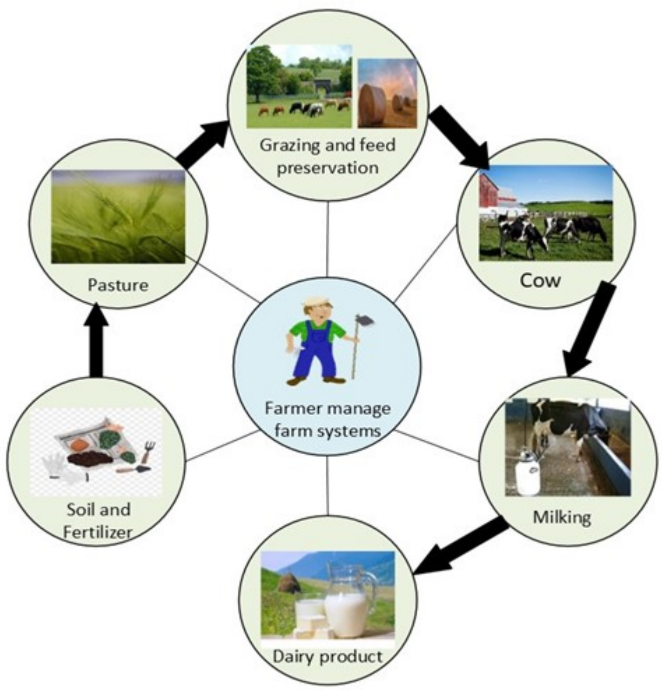

Fig. 1. Dairy farm supply chain from soil to society

This research is conducted as part of the VistaMilk[1] research project based in Ireland, funded by Research Ireland to enhance the sustainability and efficiency of the dairy supply chain. It is a collaboration of various research institutes and leading food and ICT companies, including Teagasc (The Agriculture and Food Development Authority) and ICBF[2] (Irish Cattle Breeding Federation). The VistaMilk project has divided the problem domain into: (i) soil and pasture, (ii) Livestock (Cow), and (iii) food. Combined, these three areas cover the entire supply chain from soil to society [3]. The initiative focuses on advancing pasture-based dairy production by enhancing connectivity along the soil-to-society supply chain through improvements in resource efficiency and the resilience and sustainability of dairy farming systems, as illustrated in Fig. 1. The quality of production in these supply chain subsystems depends on one another. For example, maintaining soil quality helps produce high-quality grass, which in turn provides animal feed to produce high-quality milk. The data from these monitoring systems is interrelated and essential to analyse to empower the farmers to optimise their practices; however, it is not utilised to its full potential due to heterogeneous infrastructure and a lack of semantic interoperability.

In this paper, we describe the development of domain-specific ontologies tailored to Irish dairy farms and demonstrate their application to achieve semantic interoperability. Therefore, the dataset is collected from ICBF and Teagasc. This dataset is used to gain an understanding of the domain knowledge by identifying concepts and properties. Moreover, the terms in ontologies align with farm data standards from available resources, such as AGROVOC and DalaLinker[4]. To demonstrate the use of ontology in interoperability, some competency questions have been designed and formalised in the ontology query language SPARQL. Finally, to evaluate the ontology, a query-based approach is used, and domain experts have validated its correctness. To address data privacy issues, a security layer has been introduced alongside ontologies to provide secure semantic interoperability in dairy farm systems [13].

The remaining section of this paper is organised as follows. Section 2 presents related work on secure semantic interoperability and research challenges. Section 3 presents the development of ontologies and query construction to demonstrate their use in achieving secure semantic interoperability across different systems and to evaluate their effectiveness. Section 4 describes the use case for grass growth prediction and presents the benefits of the presented approach. Finally, the Conclusion is explained in section 5.

II. Related Work

Semantic interoperability is a central challenge in the dairy farm industry, as it ensures data exchange with a shared understanding of the data. The lack of data sharing not only hinders growth but also impedes the adoption of new technologies [14] . Due to the complexity and diversity of data sources, there is a need for precise, real-time decision-making [15]. Traditional dairy farm systems pose significant challenges to data collection, cleansing, integration and analysis. This approach is acceptable for small systems that remain static over long periods [16]. Nowadays, with the heavy use of technology in dairy farms, data is generated from various sources, including sensors, machinery, yield assessments, quality evaluations, and fertiliser application. When this data is available in a standard format, interoperability becomes possible, allowing for the provision of valuable insights [17]. These valuable insights can help farmers utilise resources more efficiently, increase profits, and enhance productivity in an environmentally friendly manner [18] . However, achieving semantic interoperability has limitations.

According to the FAIR principles and research by [13], the following are the main challenges related to semantic interoperability, as illustrated in Fig. 2.

- Heterogeneity: Data is collected from various sources (e.g. sensors, software and machines) and stored independently in silos (e.g., soil data, animal data).
- Standards: There is no global standard for representing data across different systems.
- Governance: There is a lack of unified policies for the reuse of semantic terms.

[1]https://www.vistamilk.ie/(visited on 14July 2025)
[2]https://www.icbf.com/(visited 14th July 2025)
[3]https://teagasc.ie/wp-content/uploads/2025/05/VistaMilk-precision-dairying-from-soil-to-society.pdf
[4]https://www.datalinker.org/(visited 14th July 2025)

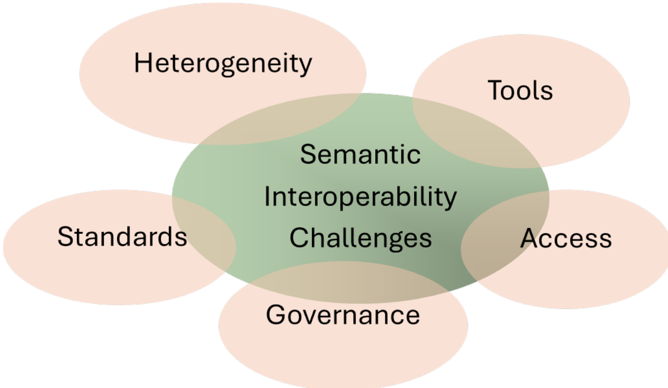

Fig. 2. The challenges of semantic interoperability

- Access: Data needs to be linked and exchanged effectively to deliver value.
- Tools: There is limited support available for developing and managing semantic interoperability solutions

In the literature, research has shown that ontologies play a vital role in achieving semantic interoperability, which provides the mechanism for a shared understanding, and the necessary vocabularies to transform data into standard formats [19]. For instance, AGROVOC, AgroPortal [20], and crop ontology are accessible via web interfaces. The AGROVOC thesaurus from the Food and Agriculture Organisation is designed to cover concepts and terminology in agriculture, forestry, fisheries, food and related domains. However, it contains an ambiguous term classification and a high number of generic terms that are not effective for precise domain-specific applications. The crop ontology encompasses a diverse range of ontologies that categorise crops based on their phenotypes, breeding, and traits. The Agroportal ontology includes both crop and non-crop ontologies, including the Animal Disease ontology and biorefinery ontologies. The Agronomy linked data by incorporates data from various silos into a single integrated dataset, though its scope is primarily focused on plants and biology. It is essential to have a comprehensive set of ontologies to cover a broader range of concepts and properties specific to applications needed in the dairy farm system of systems, including soils, fertilisers, pasture [21], livestock, and milking systems. To achieve semantic interoperability across dairy farms, a semantic data modelling technique would enhance the overall effectiveness of processes and support farmers and other stakeholders in decision-making.

The realisation of semantic interoperability is not possible without addressing the challenges of data privacy and data security. With the advent of emerging technologies and digitisation, the dairy industry generates massive amounts of data daily. Several research teams exploit data collected from farms to optimise farm processes, making them more efficient and cost-effective. Currently, researchers conduct independent research with limited data sharing due to a lack of data security and trust among stakeholders. In general, several approaches have been proposed in the literature under the umbrella of smart or precision farming. However, no sophisticated mechanism is available to address security concerns, including potential misuse of data and farmers' trust in data sharing. In the last decade, academic research has increasingly recognised these privacy concerns, proposing legislative protections and software solutions to address them [22] [23] [24]. Despite all these efforts, the dairy industry still lacks a dedicated regulatory body for data protection. Additionally, the complexity of lengthy, technical data-sharing agreements further discourages participation [13]. Therefore, it is crucial to address security concerns with the interoperability to improve the dairy industry.

III. Proposed Approach for Semantic Interoperability

Dairy farm systems comprise various interconnected subsystems, including the milking system, livestock management system, grazing system, pasture management system, and soil fertility system. Each of these subsystems generates data through various devices and applications, resulting in a highly heterogeneous environment. This heterogeneity creates challenges in achieving interoperability between systems. However, with the advent of semantic technologies, ontologies have the potential to enhance the interoperability among these systems.

This section outlines the approach to achieving semantic interoperability in dairy farming. The approach consists of two main components: first, the development of domain ontologies; and second, the design of competency questions to demonstrate the use of ontologies for interoperability and to evaluate their effectiveness. The ontology development process is shown in Fig. 3. The following subsections provide a detailed discussion of each component. Once the ontologies are developed and data is populated, they can be enabled and made accessible via a query interface, allowing diverse stakeholders, such as research institutes, private organisations, and government institutions, to collaborate and share data for informed decision-making seamlessly. Moreover, newly generated data can be populated in the ontology.

In addition to ontology for semantic interoperability, the security layer has been added to the approach, as shown in Fig. 4. The security layer provides a mechanism to preserve data privacy while enabling data sharing across interoperable systems. To understand the approach illustrated in Fig. 4, consider that the farm's data is generated and stored in databases for each farm, such as Farm A, Farm B, and Farm C. Then, each farm's data is transformed into domain-specific ontologies to represent data in a standard format for data exchange. Each farm has a collection of ontologies, including soil, pasture, and animal ontologies. The collection of these ontologies is known as a Semantic model of the farm. Now consider, on the right side of the Fig. 4, the researcher and other stakeholders access farm data from corresponding semantic models via a server-side security layer, using SPARQL queries to retrieve data from multiple farms, then merge them for use in their research models. The research output, as

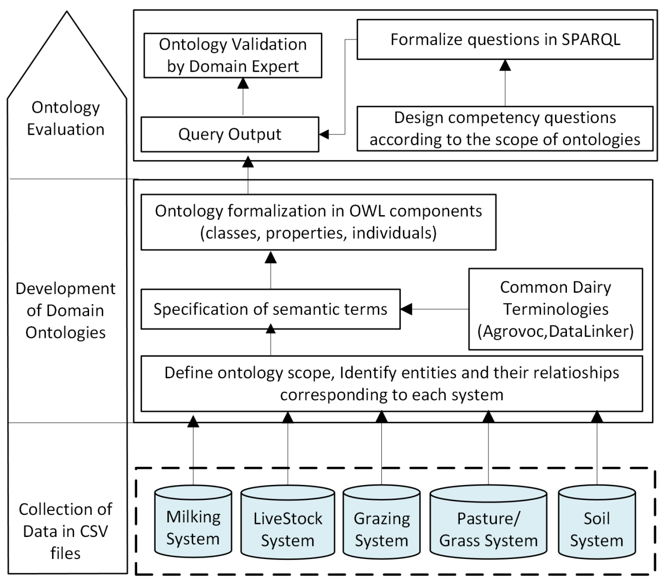

Fig. 3. Ontology Development Process

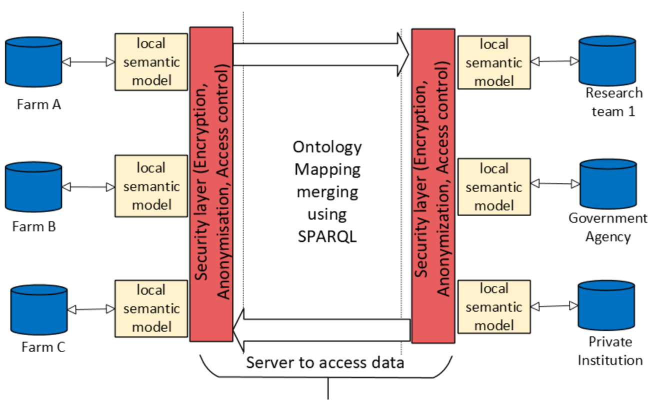

Fig. 4. Secure Semantic Interoperability Approach

feedback or recommendations to farmers, is also stored as a semantic model that farmers can access via the server through a security layer. In this way, bidirectional data exchange is used to control data dissemination in interoperable systems. Thus, a security layer enables consumers (decision support) to retrieve data uniformly and provide recommendations to farmers to manage the farm effectively. The security layer consists of data protection technologies such as encryption, anonymisation, and access control to ensure a secure, interoperable system. Encryption uses cryptographic techniques to convert information into unreadable code to protect it from unauthorised access. An anonymisation technique is applied to hide personally identifiable information from datasets. Finally, access control is configured for each user based on their role in the interoperable systems.

A. Development of Ontology

Ontology is a formal and explicit specification of a shared understanding that enables seamless communication across subsystems. In this paper, to understand the domain knowledge of the dairy farm, data resources from ICBF and Teagasc related to PastureBase[5] and ICBF[6] databases are used. To gain a deeper understanding of dairy farming in Ireland, we frequently interacted with domain experts from ICBF and the Teagasc team, including highly experienced researchers. The objective of this research is to provide a comprehensive set of ontologies for interoperability between dairy farm subsystems. However, to focus on each subsystem in detail and avoid complexity, this paper is limited to the soil and pasture ontologies. Additionally, information about the entities, such as the farm, its location, and the farmers, is incorporated to identify the farm's location and who owns or manages it. Ontology Scope: The purpose of the ontology is to enable interoperability by defining the interdependent subsystems in the dairy farm, which must be incorporated into the ontology. The soil provides crucial support for pasture growth, and healthy soil improves pasture quality. The pasture growth quality analysis requires interoperability between the pasture and the soil systems. Therefore, the scope of the soil ontology is to specify entities that define information about soil factors affecting pasture growth, and the scope of the pasture ontology is to describe the information to analyse pasture quality. Thus, soil and pasture data can be made interoperable using ontologies.

Linked to common Dairy Terminology: The ontology development has been further guided and simplified by the available structured description of standard dairy data within the DataLinker repository, which provides schema repositories of Farm-Data-Model through the efforts of the agricultural community. However, this data specification has not been approved as a standard by an international body but is widely used by the community. To leverage the available resources on standard terms, we identify the entities and properties for the ontology as found in the ICBF and Teagasc datasets and match them to the terms defined in the DataLinker schema repositories for soil and pasture systems. If the term matches, we use it in our ontology; otherwise, we define the remaining terms in consultation with experts. In this way, we linked to common dairy terminology. In defining taxonomy, it is considered the specification of generalised concepts using common characteristics of specific concepts. The Protégé[7], an open-source ontology editor, is used to model the ontology. The ontology design process is followed by iterative feedback with the domain expert team members to incorporate changes.

In the ontology design, we adopt a modularity approach, considering the different subsystems that need to be managed in the dairy farm, including the soil, pasture, Fertilisation, livestock, and milk production systems, which can be centralised or decentralised. The overall dairy farm system, comprising essential entities for analysing dairy farm data, is illustrated in Fig. 5. Each box heading represents a class name, and the

[5]https://pasturebase.teagasc.ie (visited 14th July 2025)
[6]https://www.icbf.com/the-icbf-database/(visited 14th July 2025)
[7]https://protege.stanford.edu/

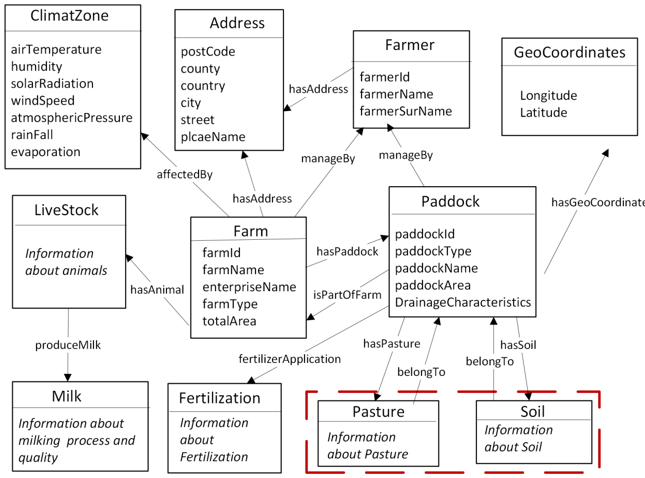

Fig. 5. Ontology Model for the dairy farm

data-type properties are listed in the box. The arrows represent the relationship between classes. In addition to these systems, other entities are essential to define, such as the farmer who manages the farm, the farm with specific attributes, location and climate conditions. The farm is divided into paddocks, consisting of soil and pasture. Each paddock is linked to its geographic coordinates to identify it uniquely.

Specification of the Soil and the Pasture ontologies: In the case of the soil subsystem, the soil ontology expresses knowledge about soil types, soil nutrients, soil moisture, soil fertility, and environmental impact on soil. Similarly, in the case of the pasture subsystem, the pasture ontology expresses knowledge about pasture types, pasture nutrients, pasture cover areas, pasture growth rates, biomass, dry matter, and the environmental impacts on pastures. Additionally, information about the entities, such as the farm, its location, and the farmer, is also incorporated into the ontology to identify the land location and the owner who manages the farm. Fig. 6 and Fig. 7 illustrate the soil and pasture ontologies, respectively. The ellipse shape represents classes, the arrows with rectangles represent data type properties, and the arrows between two ellipses represent object properties.

In the soil ontology as shown in Fig. 6, terms such as soil texture, soilMoisture, soilNutrients, soilDrainage, SoilProperties and WeatherObservation store weather update information, which includes wind speed, solar radiation, air pressure, humidity, temperature, weather condition (cloudy, sunny, rainy), evaporation, and the date. The SoilProperties and drainage are matched with the available resources with the DataLinker. The other terms, such as SoilDensity, and soilOrganicCarbon, are matched in the AGROVOC dictionary. Similarly, in the pasture ontology as shown in Fig. 7, terms such as pasture, pastureType, pastureCover, pastureGrowth, Silage, Hay, FeedHarvest, dryMatter, weight, and Nutrients matched with the DataLinker resource, whereas the term biomass matched the AGROVOC dictionary. Finally, to determine the location of the paddock, the geographical coordinates, including longitude and latitude,

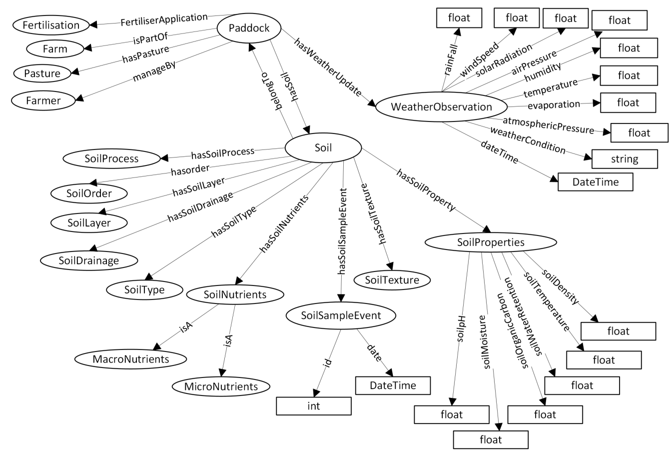

Fig. 6. The soil ontology for dairy farm

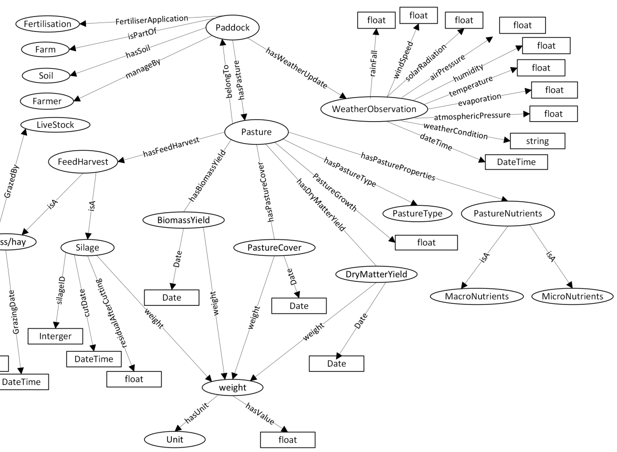

Fig. 7. The pasture ontology for dairy farm

are stored, in addition to the farm's physical address. The terms related to Farm, Farmer, and Paddock, along with their attribute, matched in the DataLinker resource.

B. Ontology Use in Interoperability and it's Evaluation

Ontology evaluation has been a longstanding challenge in ontology engineering. The authors argue that one way to evaluate an ontology is to assess its usability or applicability in the tasks it targets [1]. In this section, ontologies have been analysed for interoperability and evaluated for correctness using a query-based approach to assess their usability, verified by domain experts. In this regard, some competency questions have been designed as listed below in natural language. The sample questions illustrate the interdependencies among dairy farm subsystems. Each subsystem is modelled in ontologies to ensure consistent interpretation, facilitating interoperability to get answers to these questions.

1) Retrieve the pasture growth based on soil moisture in a Paddock (Soil, Pasture)
2) How much does the grass yield produce in a paddock of a farm in the given time interval (Farm, Pasture)

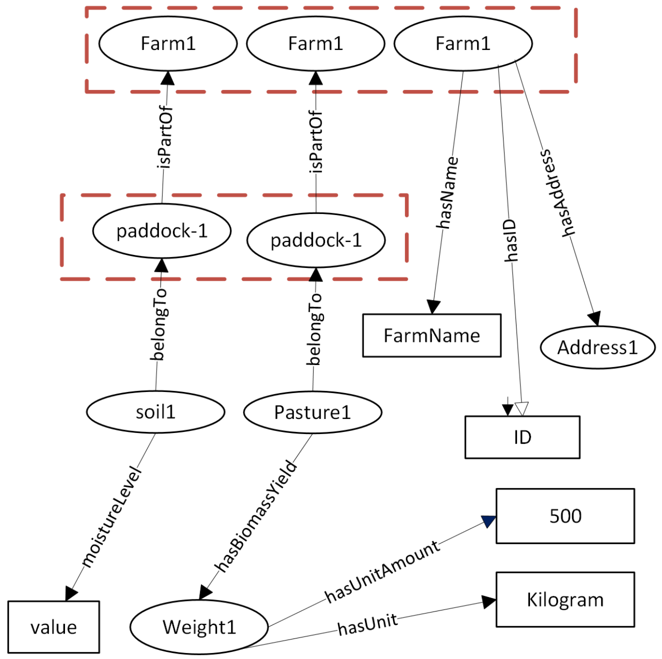

Fig. 8. The SPARQL query result as a graph

3) Retrieve soil properties and weather observations to analyse the impact on pasture growth. (Soil, Pasture)
4) List the pasture areas with low water retention and high nutrient value. (Soil, Pasture)

For example, consider question 1, which involves retrieving pasture growth based on soil moisture level. This is achieved by retrieving biomass yield from the pasture ontology and soil moisture level from the soil ontology, and further using geographical coordinates to identify the location of the Paddock.

The graph pattern retrieved by this query is shown in Fig. 8, which utilises the linked data mechanism, overlaps similar instances using a uniform resource identifier such as Farm1 and paddock-1 indicated by the red dotted line, and combines the resultant graphs. In this way, data can be accessed from different systems to operate together. Similarly, all the questions listed in Table 1 are formalised in SPARQL, an ontology query language. Finally, ontologies are used by the governance body, research institutions, and other stakeholders to access data through the query interface. On the other hand, ontology evaluation is an ongoing process that requires the development of additional questions to ensure the completeness and correctness of the ontologies.

IV. Use Case: Grass Growth Prediction

This section presents a use case that can benefit from the proposed approach. Pasture management is a fundamental part of dairy farming, ensuring that cattle have access to high-quality feed throughout the grazing season and during the in-housing period. If pastures are not well-managed, farmers will have to purchase supplementary feeds for their animals, which are less sustainable and more expensive. A key part of this management is the weekly estimation of grass growth for the next seven days, a task that demands utmost diligence and commitment from farmers. The research teams are dedicated to developing a grass growth prediction model using farm data, enabling farmers to make informed decisions.

The farm data includes paddock area, grazing and cutting dates, silage quantity, nitrogen fertilisation rate, date of fertiliser application, and other relevant details. Additionally, soil health significantly impacts grass growth, including factors such as soil moisture levels, soil temperature, weather forecasts, and other data. The researcher will predict information about when and how much fertiliser should be applied. How much grass will grow in the field? Based on the prediction, farmers can optimise grazing activity, feed management, and efficient fertiliser application.

Consider research teams that collect data for analysis from various farms, which require weekly grass growth predictions to help farmers make informed decisions in the field. Currently, to conduct the study on grass growth prediction, data is collected in CSV files sent via email. To prepare the dataset for use in the prediction process, each CSV file requires special attention to data cleaning and data aggregation, along with the additional derived variable, which is a tedious task. Different teams are working on data from the same source, but each team is assigned different variable names to maintain consistency. Thus, there is no clear description of the data, making it difficult to understand its meaning. Additionally, to incorporate changes to the process for retrieving data into a CSV file, which increases the chance of mistakes. Moreover, different teams applied different approaches to grass growth prediction using the same data in isolation, and these approaches cannot be combined to complement each other. The data ownership is not clearly described; therefore, there is a high chance of a data breach [13].

The presented approach helps to address these issues. Consider that each farm's data is described in the same domain ontologies for uniform representation to be utilised by consumers, including research teams, private institutions, and government agencies. In this process, the mapping algorithm is applied to transform data from a CSV file to an ontology representation via the API. Once the data is available in ontologies, it eliminates the need for repeated data cleaning and preprocessing, reduces the risk of errors and provides a common understanding and clear description of the data.

To maintain data privacy and security, the authentication layer is added between the ontology and consumers, as shown in the Fig 4. Each consumer has authorised access limited to their roles by restricting access to a specific part of the ontology. Moreover, the research team utilised data in a prediction model and stored the predicted values as additional variables that other research teams can access anonymously if found helpful in their projects, through the ontology API. Therefore, it must be noted that data is stored in a decentralised manner, while maintaining a unified model using an ontology and an authentication mechanism to control access.

V. Conclusion

This paper addresses the problem of semantic interoperability between different stakeholders across dairy farms in Ireland. These subsystems include soil, pasture, livestock, grazing, and milking systems, each utilising a variety of devices, protocols, and software applications, making it challenging for stakeholders across the dairy farm to access the integrated information. We proposed an ontology-based approach that builds a community consensus to represent data in a unified format as domain ontologies to achieve semantic interoperability. This paper presents the development of soil and pasture ontologies. The Teagasc and ICBF datasets are being utilised to understand domain knowledge and define the scope of ontologies. The terms used in the ontology are linked to the shared vocabulary resources provided by the DataLinker and AGROVOC. To evaluate the use of ontology, competency questions have been developed and formalised in SPARQL, and domain experts have verified the results. The Protégé tool is used to model and query the ontology. Furthermore, interoperability raises risks to data security and privacy because data sharing may expose individuals to unauthorised access and misuse of farm information; therefore, a security layer is added, incorporating enhanced security controls to protect data safety and privacy, including data anonymisation, encryption, and access controls. In the future, a comprehensive set of domain ontologies will need to be developed, encompassing livestock and milking subsystems.

Acknowledgment

This publication has emanated from research supported by grants from Taighde Éireann - Research Ireland under Grant Numbers 21/RC/10303_P2 (VistaMilk) and 12/RC/2289_P2 (Insight). The authors are also highly grateful to the Teagasc and ICBF teams for providing access to the underlying datasets and for their assistance in understanding the domain knowledge.

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