Building a Spatial Database for Agricultural Record Keeping and Management on a Regenerative Farm

by

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Dedication

To my family, friends, and farmers around the world.

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List of Abbreviations

Ag	Agriculture
CDL	Cropland Data Layer
DB	Database
FMIS	Farm Management Information Systems
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite Systems
NASS	National Agricultural Statistic Service
NDVI	Normalized Difference in Vegetation Index
PA	Precision Agriculture
RS	Remote Sensing
SDB	Spatial Database
SQL	Structured Query Language
UAV	Unmanned Aerial Vehicle
USDA	United States Department of Agriculture
USGS	United States Geological Survey

Abstract

Identified by polycultures of plants and animals, regenerative farms are made up of complex interrelated systems and face challenges with data management and record keeping. Despite regenerative farms having more complex record keeping needs than industrial (monoculture) farms, they are not well supported by existing farm management software. A spatial database can be a powerful tool for organizing, accessing, and analyzing farm data. The objectives of this research are to design and create a functional demonstration of a spatial database for agricultural record keeping that is tailored to the needs of regenerative farmers. The initial database design was informed by an extensive literature review of record keeping technologies in agriculture as well as the author's professional experience working on regenerative farms. The database's logical schema was finalized after conducting interviews with farmers and leaders of the regenerative movement in Ventura County, CA. Nine interview subjects representing five regenerative agriculture organizations participated in this study. The farms had varying record keeping practices, from memory, to spreadsheets, to Farm Management Information Systems (FMIS). A spatial database was created in PostgreSQL with the PostGIS extension and populated with archival farm data to demonstrate the database's usefulness to regenerative farmers. The data was combined and visualized through SQL queries that leveraged the relational, temporal, and spatial qualities of the farm data. While this spatial database requires technical proficiency to set up and maintain, it was found to be more effective at handling a farms' data than their current record keeping systems. Spatial databases are well equipped to handle the data needs of a regenerative farm.

Chapter 1 Introduction

Regenerative agriculture can be broadly defined as diverse farms that grow a variety of types of crops and livestock, limit their chemical inputs, and focus on nutrient cycling and biodiversity as a source of fertility (Giller 2021). Regenerative agriculture has the goal of providing food for humans while improving the natural fertility of the land. It also represents a shift away from industrial agriculture, where farms grow monocultures (i.e., only one crop type) which are extremely reliant on the agrochemical industry for fertility and pest control (LaCanne 2018). Given the numerous variables and complexities on a regenerative farm compared to an industrial monoculture farm, regenerative agriculture has unique and complex data management and record-keeping needs that can be addressed with a spatial database. The objectives of this research are to design and create a functional demonstration of a spatial database for agricultural record keeping that is tailored to the needs of regenerative farmers. This chapter discuses different farming practices (Section 1.1) which sets up the motivation and outline of the rest of the thesis (Section 1.2).

1.1. Farming Practices

Humans have been farming for many generations and have developed varied agricultural practices (Berglund 2014). This section introduces some of these farming practices and compares regenerative and industrial agriculture. It continues by discussing the intricacies and importance of farm record keeping for agricultural management.

1.1.1. Regenerative Agriculture

Regenerative agriculture is a holistic farming system that emphasizes biodiversity and nutrient cycling and is characterized by diverse polycultures of plants and animals. It advocates against chemical inputs, as most chemical inputs (e.g., pesticides, herbicides, and fungicides) limit biodiversity (White 2020). Regenerative farms aim to reduce all their external inputs and instead rely on biodiversity to create fertility. While it is no longer the way most food is grown, regenerative farming with small diverse polycultures is not a new concept. Humans have been farming this way for thousands of years (Berglund 2014).

As a foundation for life, soil is a relatively good indicator of ecosystem health. Soil is a complex mixture of minerals, water, bacteria, fungi, protozoa, nematodes, worms, and more (Saleem 2019). Healthy soil is the basis of plant fertility, as it is where plant roots naturally grow and where all terrestrial life begins and ends (Saleem 2019). Root growth fuels plant growth and plant growth produces the food that humans eat. While this is not a novel idea, it is important to remember the value of soil as much of modern society becomes farther removed from its food production.

Soil is essentially a food web, where microorganisms are constantly breaking down ("eating") dead organic matter (such as a leaf or dead roots). These organisms are often eaten by larger ones, which connects larger life forms, like worms, with single-celled organisms in the food web (Rhodes 2017). There are also living plant roots spread throughout the soil, which release sugars into the surrounding soil to encourage the growth of microbial communities (Lehman 2015). This diverse community of creatures found in healthy soil converts nutrients from dead plant material or animal manures into forms that can more readily be used by living plants. This biodiversity and the complex relationships between all life create healthy soil (Crews 2018).

Rotational grazing is a form of pasture, soil, and livestock management that leverages biodiversity to build soil and encourage plant and animal health (Savory 1983). In rotational grazing, large ungulates (e.g., cows) move frequently, grazing on plants, trampling seeds into the soil, and leaving manure wherever they go (Savory 2013). Manure is essentially organic matter (grass eaten by the cow) macerated and coated with microorganisms from inside the cow's four stomachs (Harfoot 1981). This manure adds diverse nutrients and biology to the soil, but only if there are enough living organisms in the soil to break down the manure.

While the cows rotate, other farm animals can help accelerate the manure's decomposition, such as chickens who graze a few days behind cows, eating the larger insects and larvae growing in fresh manure (Salatin 2018; Hammond 1942; Moula 2018). In the process, the chickens spread manure around and scratch it into the top layer of the soil, speeding up the manure's decomposition and incorporating it into the soil food web more efficiently. To fully take advantage of a rotational grazing system, farmers need to document when pastures were seeded, when animals have grazed each pasture, and more. Rotational grazing is just one aspect of regenerative agriculture, but it exemplifies the numerous variables at play and the importance of the relationships between those variables

In regenerative farming systems diversity is the driving force of fertility. Diversity in the food web is what connects all life, from large mammals (e.g., humans and cows) to microscopic soil bacteria. To encourage this diversity, regenerative farms often produce their own compost, grow multiple species of cover crops between orchard trees, rotate both cows and chickens daily, and support native habitat areas that do not grow crops (Rhodes 2017). Regenerative agriculture is a broad term, and every farm is unique. Therefore, the above practices are not meant as an exhaustive or required list of farm endeavors. Rather, it is meant as an overview of some of the potential variables present on a regenerative farm. Regenerative farms are complex, interdependent systems which have different organizational requirements than industrial agriculture.

1.1.2. Industrial Agriculture

While regenerative agriculture encourages diversity in its farming products to help ensure diversity in the soil, industrial agriculture operates from an opposite framework of specialization and scale. Industrial agriculture is the product of the Green Revolution which took the tenets and infrastructure of the Industrial Revolution and applied them toward increasing agricultural production. The Green Revolution was marked by the advent of genetically modified crops, chemical fertilizers, pesticides, and both faster and wider distribution networks (Pingali 2012). This type of industrial farming has been around for fewer than 100 years and has already transformed global food systems, and by extension, most humans' diets.

Since the green revolution, much of the agricultural industry has been consolidated into large monoculture farms (Fitzgerald-Moore 1996). Monocultures require chemical inputs of fertilizers, herbicides, pesticides, and fungicides to ensure that the one desired crop grows and nothing else can compete with it (Pimentel 2005). These industrial operations are thousands of acres and specialized to the point of only producing one type of agricultural good (e.g., annual crops, livestock, orchard trees, compost—no combinations) (Altieri 2017). Many operations go further and only grow a few species within a given type of food. A 10,000-acre farm that only produces corn is not uncommon in the United States, as these practices have historically been encouraged by the government through subsidies meant to ensure national food security (Kammer 2012). There are consequences to this farming system beyond its inherent reliance on the agrochemical industry (Crews 2018).

Despite their widespread use, industrial monocropping systems have negative impacts on environmental health. The environmental downside to these monoculture farms is the same thing that makes them economically efficient; a lack of diversity (Gibson 2007). While growing only one crop may streamline production and harvesting, it depletes the soil of nutrients and biology making crops completely reliant on chemical fertilizers and pesticides to survive. These added chemicals do not incorporate into the solid food web efficiently, and often runoff into nearby bodies of water (Pimentel 2005). The lack of diversity in plant species also makes the farm susceptible to widespread disease and pest damage (Paredes 2020). It is beyond the scope of this project to analyze all the economic and environmental pros and cons of industrial (large monoculture) vs. regenerative (small polyculture) agriculture; but one may rest assured that these are different approaches to land management, each with their own unique challenges.

1.1.3. Farm Record Keeping

Accurate and complete records help businesses understand their operations so they can make informed decisions (Bailey 2011). Regenerative farms need to record many species of annual and perennial plant crops at varying stages of growth, track grazing routes of multiple livestock species, monitor native habitat areas, and more. Industrial agriculture is often interested in only one crop at a time, which leads to a simpler record keeping system. Records for a regenerative farm represent many entities occupying the same spaces and moving over time, so are well suited for a spatial database (Sreekanth 2013). With accurate data about farm operations (e.g., how many seeds have been planted and how well they have grown), farmers can make better management choices for both the business and ecological health of the farm (e.g., order the appropriate amount of seeds needed for a pasture at the right time). More accurate records save the manager time, labor, and money, all while helping the farm stay ecologically productive

(Sreekanth 2013). A regenerative farm is diverse, interconnected, and always changing. Its data management needs are naturally more complex than that of an industrial farm growing only one crop per season

1.2. Study Motivation

Much of agricultural record keeping research is focused on Geographic Information Systems (GIS) used for precision agriculture (PA) on large monoculture farms (Zhang 2016; Bhakata 2019). While this is a valid use of the technology, GIS and the underlying spatial databases that support the GIS can also greatly benefit small, diverse farms (Aicardi 2020; Apolo-Apolo 2020; Nishiguchi 2009). Regenerative agriculture involves many moving parts, all of which exist on the land; from crop placement and succession planting, to livestock rotation, grazing patterns, and irrigation plans (Oates 2011). These operations include significant spatial and temporal data and have many records that need to be updated regularly. Keeping data in a spatial database can help improve the completeness and accuracy of a farm's records (Sreekanth 2013). A spatial database can record the spatial relationships between different resources on a farm as well as how the resources and their management practices change over time (Milicic 2012). This section presents the study area and research goals including an outline of the thesis.

1.2.1. Study Area

The specific study area for this research is agricultural land in Ventura County, California. Agriculture is the cornerstone of the county's economy, and an important part of its heritage (Brownly 2018). Located northwest of Los Angeles, Ventura County is home to a $1.5 billion agricultural industry that supplies about 8% of the jobs and accounts for roughly 27% of the land in the county (Shirley 2008; McCluskey 1995). Figure 1 shows a map of the cropland areas in the county in 2021. The figure shows a portion of the Cropland Data Layer, which is a product of the United States Department of Agriculture (USDA)'s National Agricultural Statistics Service (NASS).

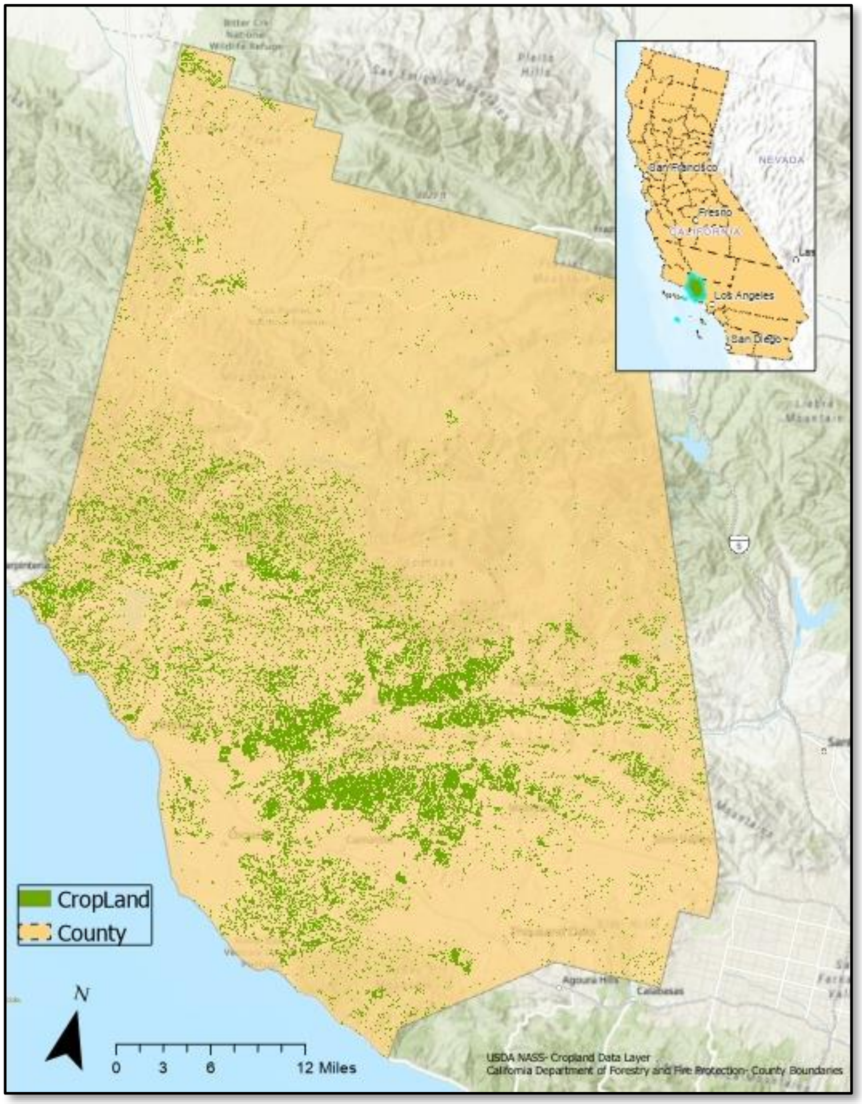


Figure 1. Map of agricultural cropland areas within Ventura County, CA.

Ventura has a mild Mediterranean climate with few frost days, which makes it suitable for growing many types of crops, but agriculture in the county is limited by low rainfall amounts (about 15in per year) and high property values (Shirley 2008; McCluskey 1995). Having worked with farms in Ventura for several years, the author has a professional relationship with the agricultural industry and knows that many of these farms are open to improving their organization and data management.

1.2.2. Research Goal

This research aims to design, build, and demonstrate a spatial database for record keeping and management on a regenerative farm. The goal is to create a spatial database that effectively utilizes the spatial and temporal nature of agricultural data to better support informed decision-making on a regenerative farm. The data can be accessed, combined, and visualized through database queries. For example, the orchard team can easily check when the livestock team move sheep, the compost team can find where the cows were two days prior (to collect manure), or the picking team can see which orchard rows have a hold on harvesting because of recent fertilization. Keeping all this data for multiple farm departments in a spatial database allows for much more detailed and complete analyses by farm managers, who may not be involved in the day-to-day work of every department. It also helps farm workers understand the complexities of the farm beyond their individual tasks.

Following this introductory Chapter 1, the next chapter (Chapter 2 Related Work) explores literature relating to farm record keeping and management systems, geographic information in agriculture, and spatial databases. Chapter 3 Methods describes the steps that went into designing this research, how data were collected, and how the database was designed and implemented. Chapter 4 Results provides the results of the farmer interviews, the final database design and implementation, and queries to access and visualize the data. Chapter 5 Conclusions and Discussion concludes with the database’s value to farmers, as well as limitations and future steps in this research.

Chapter 2 Related Work

Agriculture is crucial for human life and development. As the source of our food, agriculture is an integral part of our society, and it accounts for the largest area of land use by humans (Foley et al. 2005). Agricultural studies focus on improving agricultural management using various approaches, from national record keeping, to GIS integration and real-time productivity analysis (Aicardi et al. 2020; Dohlman 2022). This chapter outlines the methods and results of literature related to farm record keeping and management (Section 2.1), geographic information in agriculture (Section 2.2), and spatial databases (Section 2.3).

2.1. Farm Record Keeping and Management

Documenting and maintaining agricultural practices and production amounts on a farm is essential for the success of the farm operation. Good data management is based in creating efficient methods for storing, organizing, retrieving, and analyzing data. This section summarizes the evolution of record keeping on farms and introduces modern Farm Management Information Systems (FMIS).

2.1.1. Evolution of Record-Keeping

Agriculture has been around much longer than computers, and historically farmers have kept their records without using any form of electronics. Agricultural record keeping starts simply with memory, as many farmers rely on tradition and experience to understand their crops (Kok 1985). When more detailed data is required, farmers may write in diaries or daily agendas. These diaries (as shown in Figure 2) consist of a few words written in a small notebook for each day telling what was completed that day, what equipment was used, and any technical notes about the work (Joly 2011). Even today many agricultural operations, especially small farms, rely on their workers' individual knowledge, memory, and hand-written notes to keep track of relevant information (e.g., planting dates, nutrients applied, number of days grazed) (Norvell 2003; Pers. Com. Steve Sprinkle).

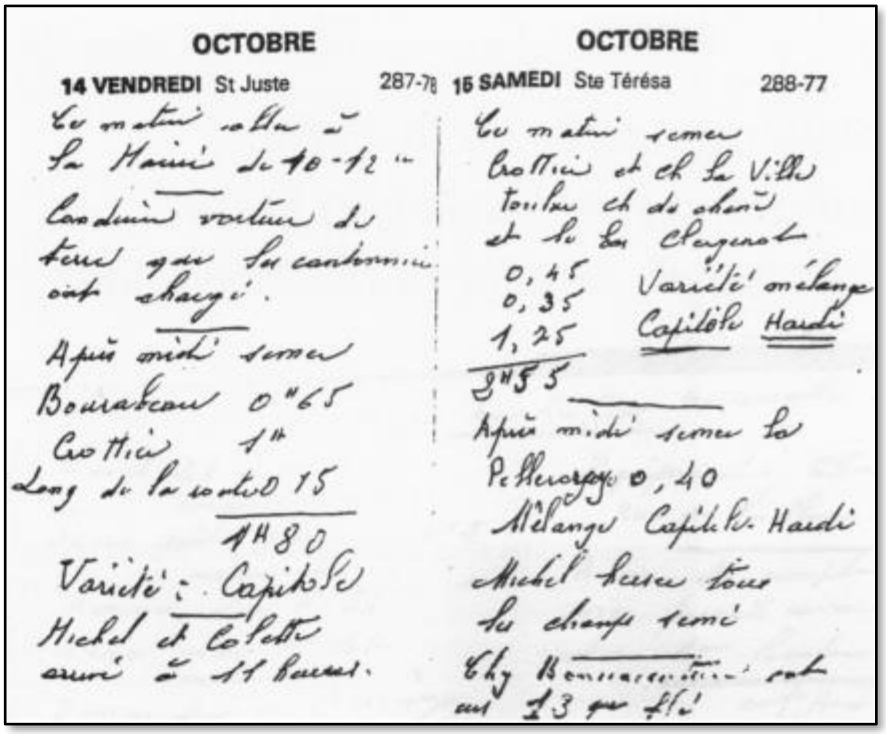


Figure 2. An “agenda” of agricultural records kept by a French farmer in the 1970’s (Image Source: Joly 2011).

The next step up in record keeping technology is using simple digital spreadsheets to record information (Claiborne 1991; Grisham 2007). Spreadsheets hold data in cells that are organized into columns and rows (Van de Aalst 2018). This data can be manually input into a cell or be calculated based on custom formulas using the data in surrounding cells (Van de Aalst 2018). This is an improvement over mental and paper notes, but the spreadsheets essentially function as a more legible version of handwritten notes and cannot efficiently handle large amounts of data (Van de Aalst 2018). Some information is not recorded systematically, and that knowledge often leaves the farm with the worker. This can be especially problematic given the high employee turnover among farm workers caused by the inherent seasonality and traditionally low wages of farming (McCluskey 1995). Multiple record keeping systems (e.g., memory, handwritten notes, and spreadsheets) are often all in place at the same time within the same farm, and that patchwork of systems leaves information falling through the cracks (Rane 2017). This jumbled record keeping results in a lot of information and data that rarely stays organized enough to use seasons later. A well-designed spatial database could change this organizational standard and help farmers better understand and take advantage of the complexity and interdependence that fuels farming (Sreekanth 2013).

The improvements in agricultural efficiency brought by increased record keeping have been studied for over 30 years. Since the early days of computers there have been advocates of using electronic databases to store more complete agricultural records and improve a farm's productivity (Kok 1985). A database is the foundational framework for computer-based data organization and can be useful for agricultural record keeping. The simple database schema in Figure 3 shows an early example of a database designed for agricultural records (Kok 1986). The entities (things being tracked by the farm) represent Parcels, Crops, and Treatments. Treatments are applied to Parcels and Parcels are seeded with Crops. The full database schema developed by Kok represents over 20 farm related entities with dozens of attributes and relationships. Kok's database schema is effective for what it was built for, and accounts for many parts of a farming operation, but it does not utilize the spatial relationships between entities. It is also not designed to handle grazing records or multiple species of livestock animals.

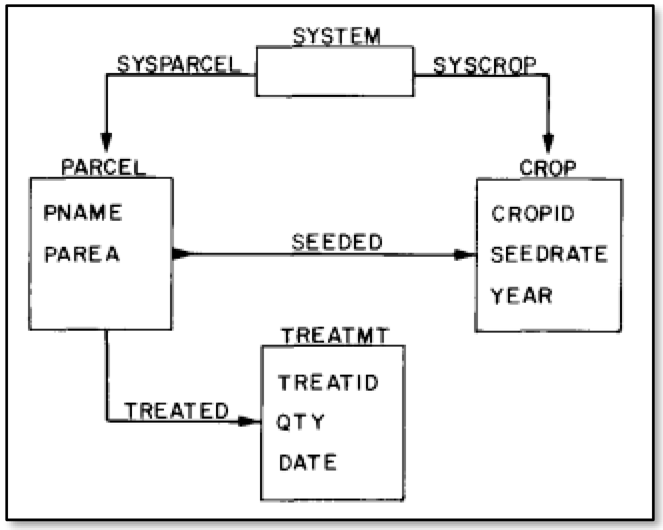


Figure 3. Section of a database schema to hold agricultural records. Boxes represent entities, their contents are attributes, and the connecting lines are relationships. (Image Source: Kok 1986).

Despite the many technologic advances in record keeping, these advances have not all been fully adopted in agriculture. Grisham's (2007) study of record keeping technology adoption was based on interviews with farmers and found that 22% of Louisiana dairy farmers do not use computers at all in their record keeping. The study found that improved data management and recordkeeping can benefit small farmers and increase farm efficiency and profitability (Grisham 2007).

2.1.2. Farm Management Information Systems (FMIS)

With the rise in computational power and efficiency of computers, companies have developed software to integrate a farm's record keeping with its larger management information systems. Farm Management Information Systems (FMIS) are computer information systems specifically developed for agriculture. Tummers et al. (2019) and Guia et al. (2021) review the state of popular Farm Management Information Systems (FMIS) from 2008 to 2018 and 1998 to 2019, respectively. They find that FMIS are generally specific to certain domains (such as dairy farming or orchard crops). The studies identify the major features of existing FMISs (e.g., crop management, data processing, accounting) and some of their obstacles, including cost, data size, and understandability. These FMIS do not have spatial components to their entities and if so, it is limited to only a few of the entities. Due to a lack of spatial data, features on the farm cannot all be easily mapped, and their attributes cannot be spatially joined and related. The specificity of these systems is an issue, as they are only equipped to record certain departments (Tummers et al. 2019). To keep track of livestock, orchard trees, habitat plantings, compost, and all integral components of a regenerative farm, would require multiple FMIS.

2.2. Geographic Information in Agriculture

The introduction of Geographic Information Systems (GIS) represents a pivotal phase in the effectiveness of computers for farm management. GIS are computer- based tools to store, visualize, analyze, and interpret geographic data. A GIS is equipped to organize and store farm data because of its analytical and visualization capabilities (Norvell 2003). Farm data is also particularly suited for GIS because the features represented exist over a large area of land, which makes them ideal for spatial analysis (Milicic 2012; Palisson 2010). This section describes how remote sensing (RS) technologies have been applied to agricultural record keeping. It also introduces GIS integration with farms and the concept of precision agriculture.

2.2.1. Remote Sensing for Agricultural Record Keeping and Analysis

Remote sensing (RS) has been extensively utilized within the agricultural context, from images to multispectral analyses, lidar, and more. RS involves any kind of measurements from sensors taken far from the phenomenon being measured (Weiss 2020). The most common type of RS data is imagery, though there are many other forms of data and many spectral wavelengths beyond what is visible to the human eye that can be studied through RS (Yao 2019).

Remote Sensing information can be used to document and record what happens on a farm. Detailed organization of RS measurements can bring intriguing new insights to farmers. Flynn (2006) examines the potential of using the Normalized Difference in Vegetation Index (NDVI) (calculated from multispectral RS imagery) to assess the suitability of land as pasture to feed grazing animals. Aicardi et al. (2020) describes a python customization for farmers that analyzes drone imagery and performs orthometric corrections for use of the imagery in real-time field analysis. Apolo-Apolo et al. (2020) similarly used unmanned aerial vehicle (UAV) imagery as the basis for a program that estimates apple tree health and expected yields. All these studies use RS to document conditions on a farm and inform agricultural decision-making.

2.2.2. GIS Integration with Farms

Having farm information recorded and organized allows a farmer to manage a large area of land and easily identify exceptional problem areas to work on. Norvell (2003) further developed this idea, describing how Geographic Information Systems (GIS) can be integrated with farm data to enhance farm management and record keeping. Norvell describes the improved efficiency in recording, storing, retrieving, and communicating farm information that comes from record keeping with GIS. Continuing this decades long trend of improving agriculture with technology, Inwood (2019) identifies numerous computer apps for farming that help improve the sustainability of agriculture. The apps address various aspects of the agricultural industry including regulatory compliance, equipment optimization, information management, product tracking, spatial mapping, and more. All these apps improve the documentation and organization of agricultural data.

Nishiguch and Yamagata (2009) showcased how GIS can be applied on farms to improve agricultural productivity. Their study analyzes a GIS that manages data about farm products, yields, soil type, fertilizer usage, and more, all linked to locations on the farm. Nishiguch and Yamagata (2009) found that GIS records are more effective than ledger-based management systems (e.g., spreadsheets) for crop planning and productivity analysis. Bligaard (2014) discussed a similar GIS-based FMIS for planning and documenting agricultural production. Bligaard (2014) used Microsoft SQL Server Database Management Systems to build a production database and incorporate that into a mobile application for use on farms in Denmark. This database tracks and analyzes soil conditions (e.g., soil temperature, soil moisture), pesticide use, fertilization rates, and more. This FMIS is hosted online and stores information on over 80% of the farmland in Denmark (Bligaard 2014).

2.2.3. Precision Agriculture

Precision agriculture (PA) involves detailed computer record keeping of agricultural assets and can represent a wide variety of technologies (Lindblom 2016). It generally involves taking consistent, detailed measurements of the land and using that data to inform agricultural management practices (Zhang 2016). A PA system is a comprehensive system with many different technologies working together, including databases, RS, FMIS and more.

An et al. (2003) designed a GIS for PA that includes a database structure for four types of data: weather, soil, crop, and farming practices. The attribute data are held in their own data tables and separately related to a spatial database which stores GPS coordinates and spatial data. This database structure represents one of five modules developed by An et al. (2003). The PA application also covers data collection, spatial interpolation, general GIS, and decision-making support modules. Databases and technologies used in PA can be adapted and applied to small diverse farms, but the financial cost might be significant (Álvarez 2008; Zhang 2016). While PA technology can be valuable to the agricultural industry, it is too complex a system and the cost is too high for many smaller farms.

2.3. Spatial Databases

A spatial database allows users to record, store and manage data with locational attributes. While often used in regional, continental, and global studies, spatial databases can be effective at recording smaller areas such as individual farms (Milicic 2012). Spatial databases underly many of the spatial technologies discussed earlier in this chapter (e.g., RS, GIS) and can be used for broad scale agricultural record keeping and farm management. The end of this section discusses some open-source solutions to farm management that rely on spatial databases.

2.3.1. Agricultural Record Keeping with Databases

Current and historic agricultural data informs decision-making at all levels of government, many of which keep robust agricultural datasets. The Agricultural Baseline Database (ABD) is a custom query application that is built and maintained by the United States Department of Agriculture (USDA) (Dohlman 2022). It holds agricultural productivity data and statistics for the entire nation for government and public use. This database is used for agricultural data organization and recordkeeping to monitor and improve agriculture in the U.S. As a federal database, it focuses on the yearly economics of the entire industry rather than on individual farm management, so it is most useful for broad analyses of regional agricultural productivity on the county and statewide scales.

Internationally, many countries around have their own databases to record agricultural production. The Fars Comprehensive Agricultural Database (FCADB) is a similar documentation effort to ABD but taking place in Iran (Kherad et al. 2013). Developed by the Fars Agricultural Institute, the FCADB integrates agricultural data with climate data, soil data, and survey responses. This database is used for yearly country-wide agricultural assessment and planning rather than individual daily farm management.

Another role that databases can play in the agricultural industry is for land planning. Álvarez et al. (2008) presented a land planning and classification approach for dairy farms in Spain that uses Microsoft Access Database with Excel for ease of data entry. Alvarez combined regional agricultural statistics, land cover, and population data all in the same database. The database helps inform governmental decision makers on current farming practices as well as where to develop new agricultural land.

2.3.2. Spatial Databases for Farm Management

Spatial databases are the foundation of GIS, and they are particularly effective at representing features that exist over space and time (Sreekanth 2013). Agriculture represents many features that fit those categories, such as a cow which is born, travels around grazing throughout its life, and then dies. The spatial relationship between some of a farm's features (e.g., how close the cows are to the chickens) changes frequently and is extremely relevant to everyday farming operations (Oates 2011). This type of spatial database is useful for reviewing past data, for example, to know how many days a particular pasture has been grazed each season. Spatial and temporal relationships can be leveraged by a GIS to produce higher quality and more accessible data, which can help inform managerial decision making for better agricultural land management (Norvell 2003). The starting place for getting these features integrated with a GIS is recording their respective attributes in a spatial database (Yeung 2007; Zhang 2008).

While not specifically designed for agriculture, Motyka (2018) proposes a physical design of a spatial database for documenting and managing landscape irrigation systems on a college campus. Figure 4 shows the data structure that she proposed including pipe mainlines, valves, sprinklers, irrigation zones, and more. Documentation of the location of irrigation lines and valves is extremely useful for water management (e.g., to locate a broken line), especially in areas with limited rainfall like Ventura County (Motoyka 2018; Shirley 2008). A spatial database recording irrigation information can be applied to a farm's overall record keeping system.

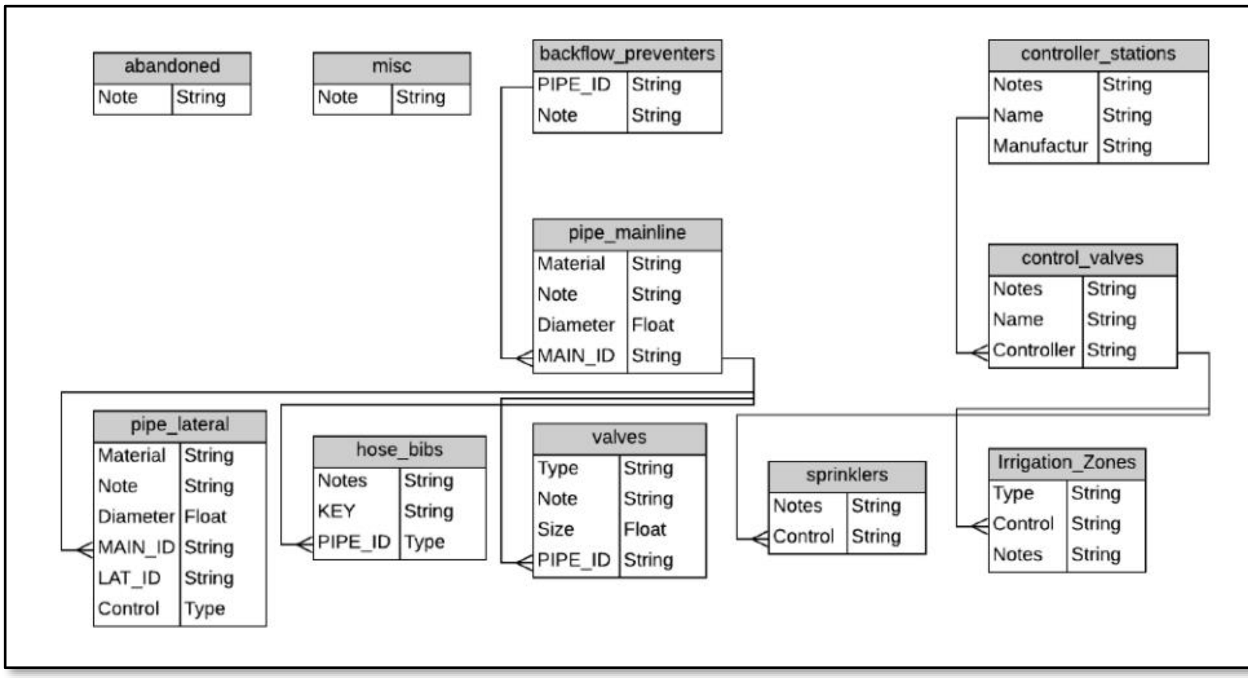


Figure 4. ERD of database for management of an irrigation system (Image Source: Motyka 2018).

Magaya et al (2017) proposed a spatially based record-keeping prototype for farmers. This database was created in Microsoft Access, and although it was not technically a spatial database, the information was linked to a spatial data table prepared in ArcGIS 9.3. User requirements were determined by semi-structured interviews and discussions with potential users, which helped in the database development. Mayaga et al. (2017) identified three main entities to track: Crops, Fertilizers, and Pest Management. Each of these entities was assigned numerous attributes to describe them, such as planting dates and harvest amounts. Upon further development, Mayaga et al. (2017) also included weed information and rainfall amounts. To spatially relate these entities, they created another entity of crop fields. They include a Field_ID in each table as a foreign key to spatially link the tables, as shown in Figure 5.

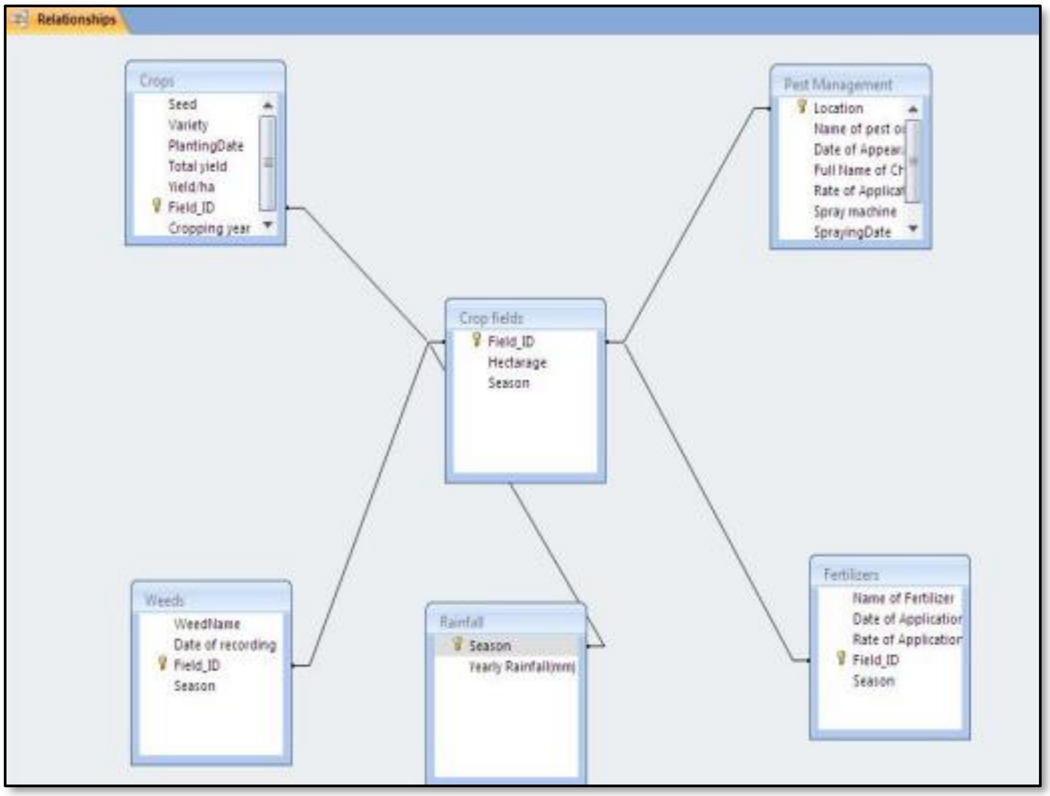


Figure 5. Entity Relationship Diagram for spatially based farm record keeping (Image Source: Magaya 2017).

2.3.3. Open-Source Farm Management

While not widely popular, there are open-source farm management programs based in spatial databases. Founded in 2016, FarmOS is an open-source web application that aims to provide a standard platform for agricultural data collection and management. There is ample documentation on their website (https://farmos.org/), which describes the data model used by the program and eight types of records including assets (entities), logs (treatment and harvest records), data streams (real-time sensor updates), users (personnel), and more (Stenta, 2022).

FarmOS is equipped to handle individual farm data as well as more regional data and is based in a PostgreSQL database. It supports dozens of features and requires significant coding experience to host, set up, and maintain.

Open Technology Ecosystem for Agricultural Management (OpenTEAM) is another open-source farm management project founded in 2019. It is a relatively new project that is well funded and growing with the goal of providing agricultural leaders with accessible, interoperable technological tools to access agricultural knowledge and build soil health (Canning 2019). These range from decision support tools to remote sensing tools and more, and while databases are not explicitly mentioned on their website (https://openteam.community/), many of the technologies they advertise (remote sensing and observation tools, agroecosystem models, interoperability) are based in spatial databases (OpenTEAM 2022).

Chapter 3 Methods

The main work of this thesis involved designing, creating, and populating a spatial database for individual record keeping of regenerative farms. The database represents dozens of entities (physical objects on the farm), attributes (relevant information about said entities), and relationships (how the entities are related and ways they can affect each other). This chapter starts with an overview of the research design (Section 3.1) followed by describing how qualitative and quantitative data were collected and prepared (Section 3.2). Section 3.3. focuses on how to design the database, and Section 3.4. outlines the methods for creating the database and accessing the data.

3.1. Research Overview

This research is connected to the wider community through input from local farmers. Open-source software was used for the research to be easily replicable. This section gives an overview of the research design of this thesis starting with a summary of the workflow and following with some software considerations.

3.1.1. Workflow

The process of demonstrating a spatial database for regenerative farmers was separated into three phases: conceptual database design, logical database design, and database implementation. Figure 6 shows these phases and represents the general workflow of this thesis.

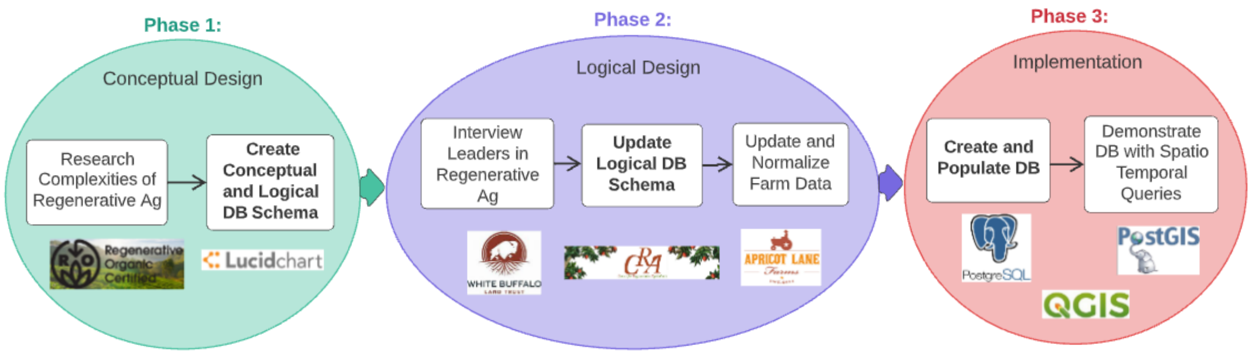


Figure 6. Workflow diagram showing the general steps required to create the demonstration database (DB) for this thesis.

This research started by exploring the complex structure of regenerative agriculture using literature review, focusing on finding approaches to keep records and store data efficiently (**Phase 1**). During this first phase, a conceptual database design was created. During **Phase 2**, the author interviewed local farmers in the regenerative agricultural community in Ventura County, California about their current record keeping systems, data analysis needs, and general farming practices. The acquired information was used to update the initial logical schema before moving to database implementation in **Phase 3**. Archival farm data from local farmers was cleaned and edited to use in an example database. The spatial database was populated, and queries were performed to demonstrate the various use cases of the spatial database for an individual regenerative farm.

3.1.2. Software Considerations

The design of a database starts with the type of database and choice of software. A web-based diagramming tool Lucidchart was used in the early phase of the database design for diagraming and modeling steps for both conceptual and logical database diagrams. Since spatial objects and their relationships are essential for agricultural operations, an object-relational database that supports spatial data types such as SQL Server, PostGIS, or Esri Geodatabase was required. Considering the accessibility to farmers, a PostgreSQL database management system (DBMS) with a PostGIS extension was chosen for this research.

PostgreSQL V14.1, also known as Postgres, is an open-source relational database software. Postgres has an active user community for troubleshooting and is well maintained. Postgres was chosen because it is free, robust, reliable, and can support spatial data types and databases (with the PostGIS extension). As an open-source software, it is easy to experiment with on any computer, and could be implemented by a farm for no cost. The database can also be copied, shared, and edited to meet the needs of a specific organization. With the spatial extension PostGIS, Postgres has efficient integration with other open-source programs including QGIS which is particularly useful for visualizing and analyzing spatial data. PostgreSQL, PostGIS extension, and pgAdmin interface (for working with data in Postgres) can all be downloaded for free in a bundle, at which point the physical database creation can begin.

3.2. Data Collection

Data for this thesis were collected as qualitative interview results and quantitative archival farm records. This section discusses the methodology of the interviews and how the resulting data were prepared to use in the database.

3.2.1. Interviews Methods

Interviews with farmers and leaders of the regenerative movement in Ventura County were conducted to understand their farming practices and data management needs. The interview subjects were also asked for copies of archival farm records. A set of questions were designed prior to interview and detail notes were taken during the interview.

While there are numerous ways to organize and conduct an interview, this thesis uses an individual semi-structured interview procedure. Semi-structured interviews involve topics that are prepared in advance but use open ended questions (Fox 2009). This type of interview is useful for collecting attitudinal information and opinions, but difficult to establish uniform responses; semi-structured interviews require interpretation before being compared and analyzed.

In this research, regenerative farm is defined as polyculture farming under 1000 acres. Farms and regenerative organizations were identified through online research as well as the author's professional connections in the regenerative farm industry. Thirteen farms and regenerative organizations around Ventura County were contacted via email in January 2022 to request for interview participation. These farms included: Apricot Lane Farms, Casitas Valley Pastures, Churchill Orchard, Deardroff Family Farms, Earthtrine Farm, Farmer and the Cook Farm, Kenter Canyon Farms, McGrath Family Farms, Ojai Center for Regenerative Agriculture, Ojai Roots Farm, Sow a Heart Farms, Underwood Family Farms, and White Buffalo Land Trust. Follow up phone calls were also made to organizations that did not initially respond.

Phone, video, and on-site interviews were conducted in January 2022. The interview questions were focused on the following three topics:

a. General farming practices: e.g., what size is your farm? What do you grow?
b. Current data collection and storage methods: e.g., what information do you need to know about each crop? Do you record location information?
c. Data and analytical needs: e.g., what type of analysis do you use? what is lacking in current data management?

A review from the Institutional Review Board (IRB) was requested for both archival farm records and interview questions, and an IRB exemption was officially granted by the USC Office for the Protection of Research Subjects on December 17, 2021. The social behavioral IRB protocol, approved exemption, and full interview script can be found in Appendices A, B, and C.

3.2.2. Data Preparation

The participants' responses to the interview questions were documented, analyzed, and used to revise the initial design of the spatial database. The interview notes helped finalize the database's entities and attributes to ensure the database's relevance to farmers in Ventura County. Individual participants' and their feedback were kept anonymous in this thesis.

Test datasets of a farm's records were acquired from interview participants, and prepared and normalized to fit the structure of the finalized ERD. The datasets were sourced from farms as spreadsheets, maps, and images of paper notes. Attribute data was reorganized into spreadsheets to be imported into the database as .csv files, and spatial data was created as shapefiles in QGIS to be imported to the database using a PostGIS import tool. The datasets were edited, normalized, and referenced to location information before integrating into the spatial database. For data not available in the existing farm records, supplemental data were created by the author to prove the database concept. The geographic locations of the farm data used in this database were moved to a different site within the county that has similar terrain. This was done for privacy concerns, and to easily aggregate data from multiple farms.

3.3. Database Design

The design is an essential part of any database as it determines how and what information the database can handle. This section discusses the initial conceptual and logical designs for a spatial database of agricultural records and goes over the choice of data types used. The logical design was updated in Chapter 4 to incorporate interview results.

3.3.1. Conceptual Design

A major focus of this work was to determine what types and forms of data should be collected by the database in the first place. The author relied on both academic research and his professional experience in the regenerative farm industry (i.e. working on a regenerative farm for four years) to create a conceptual design of the database and entities to be recorded. These entities represent a farm's records and can be divided into five main groups classified as follows:

- The **Crops** class represents any plants that are being documented by the farm.
- The **Livestock** class represents all records pertaining to the animals on the farm.
- The **Fertility** class documents compost production and other fertilizer applications.
- The **Infrastructure** class details the roads, fences, buildings etc. throughout the farm.
- The **Personnel** class records employee information.

Table 1 demonstrates the initial conceptual framework and shows the general categories of data that need to be collected and recorded in a database for regenerative farm management. Each of these five groups – crops, livestock, fertility, infrastructure, and personnel – would be made up of specific entities that represent physical resources on the farm. Each of the entities (identified in the right-hand column of Table 1) would contain numerous attributes and must be normalized for efficient data storage and retrieval.

Table 1. Conceptual framework of agricultural features in a regenerative farm database.

Groups of agricultural features	Entities within group
Crops	Garden, Orchards, Habitat
Livestock	Cows, Chickens, Bees
Fertility	Compost, Fertilizers
Infrastructure	Buildings, Roads, Pastures, Irrigation
Personnel	Owner, Employee, Contractor

As these entities needed some relevance to the overall system, the relationship classes and cardinality between them were defined. Attribute relationships were identified, but all the elements also inherently have some type of spatial relationships that could be used to combine them.

A basic bubble diagram was created to show the conceptual database design (Figure 7). This bubble diagram is the basis for creating a Entity-Relationship Diagram (ERD) for the spatial database (Figure 8), which eventually becomes the logical schema (Figure 9).

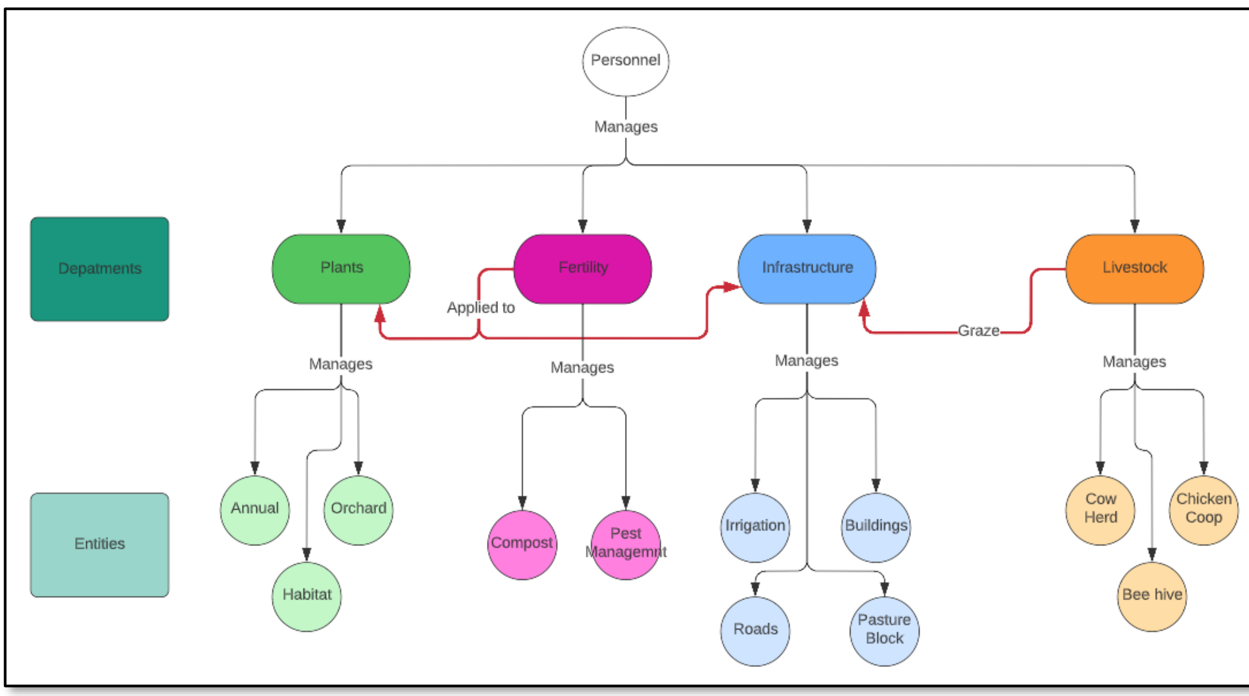


Figure 7. Bubble diagram of major departments in diverse farms, the entities they manage, and some of their relationships. Farm departments are shown by their color.

Figure 8 is the initial conceptual ERD that illustrates the entities, attributes, and their relationships. For example, an entity relevant to agricultural production could be a single Cow; this entity (i.e., Cow) may have attributes such as the herd or breed of the cow, or its birthdate. The Cow entity may also have a relationship with an entity of Pastures where that Cow "grazes" a pasture. Figure 8 is still a relatively simple idea for a spatial database of small farm management.

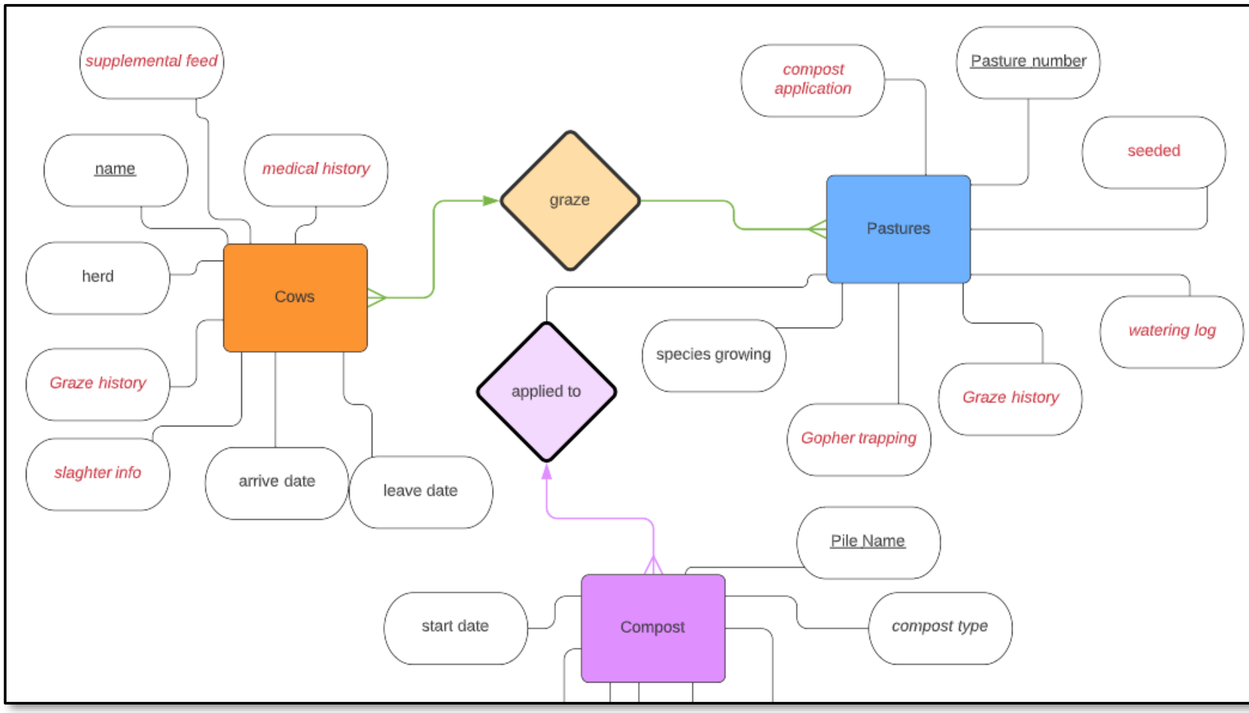


Figure 8. Conceptual ERD of a spatial database for regenerative farm management. Squares represent entities, ovals are their attributes, and diamonds show the relationships between entities.

3.3.2. Logical Design

The entities in the major groups were further developed by listing potential attributes and the types of data that are appropriate for describing those attributes. For example, an attribute could specify the breed of each cow and its birth date, and a compost pile attribute may show its weekly temperatures or its component material. The data type of each attribute was determined based on the uses of that attribute. Attributes representing words used character types, and attributes representing numbers or dates used numeric and temporal types.

Relationships among various data were identified such as “employees” that work on “CompostTurns”, or “Cows” which are part of a “CowHerd”. The “CowHerd” is linked to

"HerdGraze" events which occurs on "Pastures". Those "Pastures" can also overlap with "CoopGraze" (where chickens are grazing) or "SeedSpread" where seeds have been distributed, or even "CompostSpread" where compost fertilization has occurred. All these relationships are defined with Primary and Foreign Keys. More details of these entities, attributes, and relationships can be found in Figure 9.

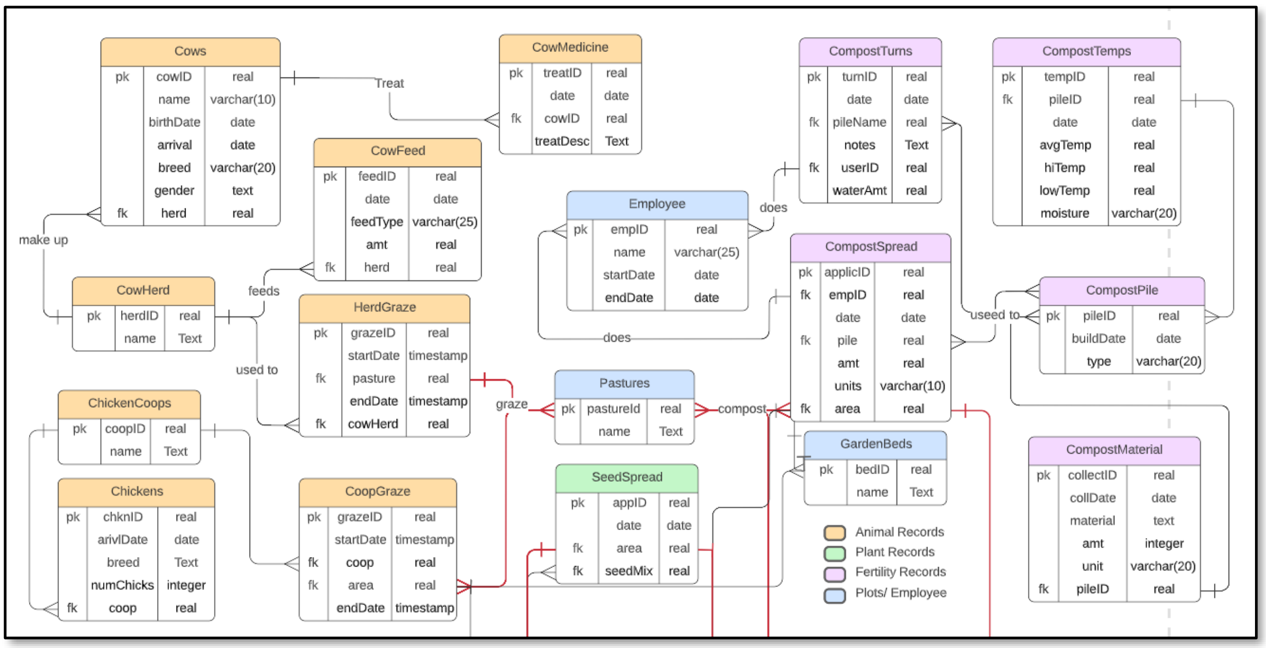


Figure 9. Early stage of logical ERD for spatial database of farm records. Departments are represented by different colors.

Spatial relationships are not explicitly shown in Figure 9 but exist between anything that has or is connected to a "geometry" type (spatial) attribute. Each spatial attribute defines a location and can be related to other locationally referenced data in the database. The more spatial data in the database, the more spatial relationships naturally exist.

3.3.3. Data Types

The final logical schema of this spatial database used five main data types: text, numeric, date, timestamp, and geometry. The first four are defined in the PostgreSQL documentation and geometry is defined in the PostGIS documentation (PostgreSQL 2022; PostGIS 2022). The decisions on data types to use was informed by farmer interviews and drew heavily on the online documentation cited (PostgreSQL 2022; PostGIS 2022). The “text” data type in PostgreSQL can represent any length string. Some other data types considered over “text” were “varchar()” and “enum”. The “varchar()” stands for variable character which controls the length of the string input. Unlike some other database systems, there is no difference in performance between “varchar” and “text” in PostgreSQL. Data of the “enum” type must match a list of acceptable strings that is created separately in the database. This can be useful for attributes such as animal type which would always be one of a few options (cow, chicken, or bee for example). Ultimately the “text” type was chosen over “varchar()” and “enum” data types to increase the flexibility and limit the restrictions on data entry.

The “numeric” data type, used for most of the attributes that represent numbers, has a variable storage size depending on the size of number being stored and can accommodate up to 131,072 digits before the decimal and up to 16,383 digits after the decimal. While numbers can technically be displayed in strings within the "text" data type, “text” data are not recognized as numbers and cannot be used with any mathematical operations. An alternate option for storing numbers is the “integer” data type which is four bytes and can store whole numbers (no decimals) between -2,147,483,648 and +2,147,483,647. The “real” data type is another option as it is four bytes and stores numbers up to six digits (including decimals). The “real” data type is inexact, so while appearing to function well, it cannot always be relied on for mathematical operations. In this spatial database, the “numeric” type was used over “integer”, “real”, or other number-based data types to keep open the flexibility to use decimals and mathematical operations.

This database also holds temporal information about dates and times, which are given their own data types to differentiate them from numbers and strings. The “date” type is four bytes and holds a calendar date (month, day, and year). This data type represents actual dates on the calendar and can be used to identify when things happened. Another data type for storing dates in this database is “timestamp” which is 8 bytes and records a date along with a time of day. This is useful for phenomenon that occur multiple times per day and for more detailed tracking of time elapsed. Having dates recorded in the proper data type allows for temporal queries which greatly enhance the analytical capabilities of the database.

The “geometry” data type holds locations based on a projected coordinate system and is defined in the PostGIS extension. “Geometry” is a spatial data type, and its inclusion makes this a spatial database. Data of the type “geometry” can represent points, lines, polygons, multipoint and more. The data of this type is defined in a given spatial reference system and can be combined and accessed through spatial queries. Alternatively, the “geography” data type holds geographic location stored in geographic coordinates. Geographic coordinates account for a spherical model of the earth and cannot be used directly with planar measurements. The “geometry” type is used in this database instead of “geography” because a relatively small area is being represented (a few hundred acres), and planar measurements and calculations are more useful to farmers.

3.4. Database Input and Access

Once the logical database design was updated from farm interviews, a PostgreSQL spatial database was created. This section outlines the database creation steps and introduces how to input data and access that data through queries.

3.4.1. Data Input

The spatial database was created with the needs of regenerative farmers in mind. It was created based on the finalized logical ERD that outlined each entities name, data type, attributes, and primary/foreign key relationships. A PostgreSQL server was downloaded and set up in the author's computer, SQL queries were used to create an empty database, and the database was ready to be populated with data.

The most basic way to input data into the database is to add values directly using SQL commands INSERT INTO and VALUES as shown in Figure 10. This method of data entry is time consuming for large amounts of data and is highly prone to human typing errors.

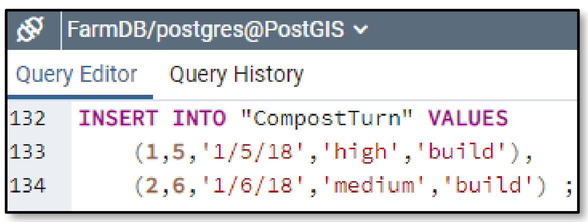


Figure 10. Image of an example SQL query for adding data into the CompostTurn table.

Figure 11 shows a portion of a CompostTurn table created as a Google spreadsheet that mirrored the structure of the table design from the final ERD. The spreadsheet was saved as a .csv file and imported to the PostgreSQL database (Figure 12). This process was repeated for each table to populate the database.

turnID	pileID	date	wtrAmt	notes
1	5	1/5/18	high	build
2	6	1/6/18	medium	build
3	7	6/13/18	high	build
4	8	7/13/18	high	build
5	9	6/17/19	high	build
6	10	3/24/20	medium	build

Figure 11. Image of the CompostTurn table that was uploaded to the database.

```
COPY "CompostTurn"
    FROM 'C:\Users\public\FarmDBData\FarmDBTables - CompostTurn.csv'
    DELIMITER ','
    CSV HEADER;
```

Figure 12. Image of SQL used to copy data from a .csv file and populate it into the CompostTurn table.

Spatial data can only be added to the database if the PostGIS extension is downloaded. The simplest way to create spatial features is to digitize them over a map by drawing the feature on a GIS (based on base map satellite imagery). This process gives the entities their spatial attributes, and the rest can be entered manually with SQL or added from an existing table. Figure 13 shows a polygon shapefile displaying farm plot locations in QGIS. The shapefile was imported into the PostgreSQL database as ‘farmplotq’ and joined to the database table ‘FarmPlot’ by the common key ‘names’ (Figure 14). This gave the entity FarmPlot a spatial attribute. More spatial data could be created to track more specific grazing or planting areas as needed, but these farm plots are enough to demonstrate the spatial capabilities of the database.

Figure 13. The spatial attributes of the FarmPlot table created as a polygon shapefile in QGIS.

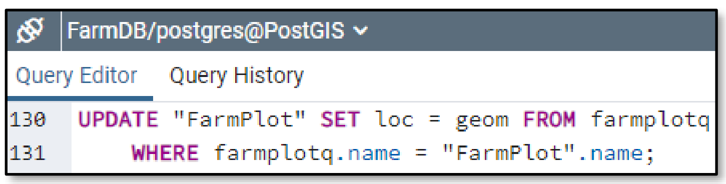


Figure 14. Image of an example SQL query for joining the spatial data from “farmplotq” to an existing table “farmplot”.

3.4.2. Querying the Database

A functioning database was created and populated with data, now it is time to interact with and visualize that data. Queries are instructions to the computer written in Structured Query Language (SQL) and are the simplest way to interact with a database. They allow the user to view, create, update, filter, join, delete data, and more. Most of the queries in this thesis focus on accessing and analyzing data once it is in the database. They are based on the SELECT statement which can display and manipulate data but does not permanently modify the underlying data values. The queries are organized into four main categories:

- Simple Database Queries access data from a single table.

- Relational Queries combine data from multiple tables.
- Temporal Queries analyze the temporal qualities of date and timestamp attributes.
- Spatial Queries combine, filter, and display data geographically using geometry attributes.

Chapter 4 Results

This chapter presents the interview results from the regenerative farm practitioners in Ventura County (Section 4.1) and describes how these interviews informed the final physical design, creation, and implementation of the spatial database (Section 4.2). Section 4.3 showcases the combination and visualization of data through various database queries.

4.1. Interview Results

Out of 13 regenerative farm organizations contacted, nine practitioners representing various departments on five farms were interviewed in January 2022 (Table 2). This section details the interview responses starting with an overview of the farms' general farming practices, followed by information about their current record keeping systems and data needs.

Table 2. Regenerative farms and organizations interviewed for this research.

Farm/ Organization Name	Established	Description/ Mission
Apricot Lane Farms	2011	Working farm integrated within an intentionally reawakened ecosystem. https://www.apricotlanefarms.com/
Farmer and the Cook Farm	2001	Farm and restaurant with focus on farmer training and consumer education. https://www.farmer-and-the-cook.com/
McGrath Family Farms	1971	Fourth-generation direct market organic farm. http://www.mcgrathfamilyfarm.com/

Farm/ Organization Name	Established	Description/ Mission
Ojai Center for Regenerative Agriculture	2002	Non-profit for environmental education. https://www.ojaicra.org/
White Buffalo Land Trust	2018	Non-profit that practices, promotes, and develops systems of regenerative agriculture. https://www.whitebuffalolandtrust.org/

Interviews with regenerative farmers validated many concepts brought up in the literature reviewed in Chapter 2 such as the importance of biodiversity and soil health. The farms being interviewed ranged in size from 12 to 1000 acres and employed between 4 and 30 farmers. The total of nine interview subjects had various roles within their farm organizations, ranging from crop manager, to compost and fertility worker, to research lead, to farm owner, to founder, and more. Interview responses including archival farm data were combined and anonymized for data privacy. This section expands on the interview results by describing the farmer's agricultural practices, record keeping strategies, and data needs.

4.1.1. Farming Practices

As expected, every farm in this study cultivated a wide diversity of farm products. Each of the farms grew dozens of species of annual and perennial crops. Most also grew fruit trees, and raised animals including chickens, cows, sheep, and bees. The two things that stood out most in these interviews were the emphasis on biodiversity and soil health on the farms. These farms all embraced polyculture farming, and diversity was integral to their fertilization, pest, and disease management strategies.

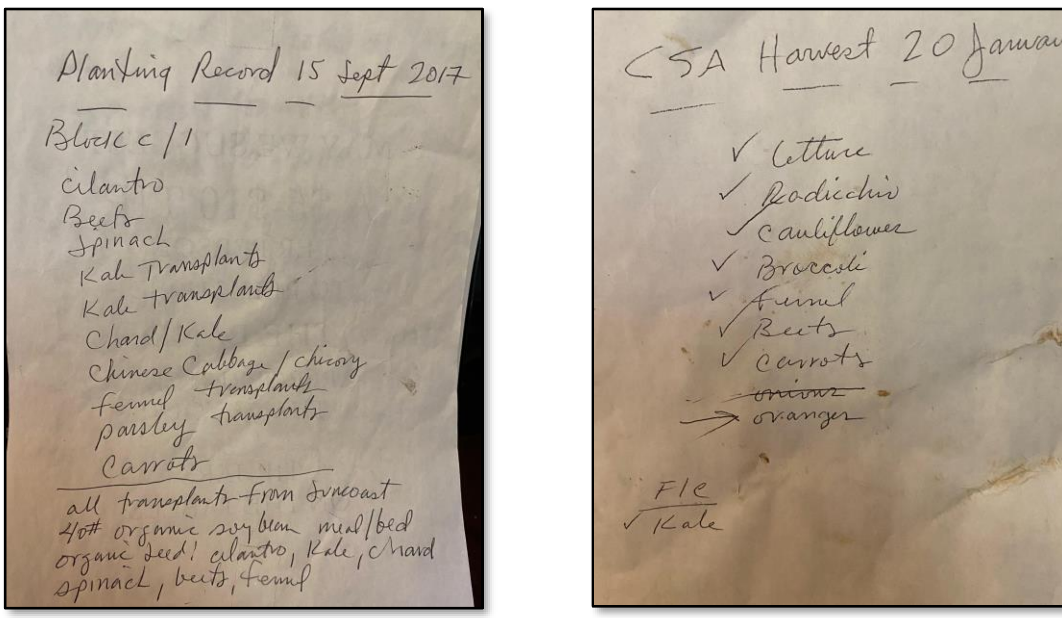
The farms overall had similar strategies for dealing with fertilization, pests, and diseases, though some had more targeted regimes than others. These farms focused on diverse cover cropping and successional planting to grow soil fertility and limit the impact of pests and diseases while maintaining areas of native habitat to sustain populations of beneficial insects. All the farms followed cover cropping and successional planting strategies and while some used very few soil amendments or inputs, other larger and more research-focused farms regularly apply compost, amendments, foliar leaf sprays, ground sprays, root drenches, and more. The amendments and sprays are targeted to specific crop varieties at certain times in their growing cycles.

All the farmers interviewed emphasized community engagement, whether through research, education, or selling directly to local consumers. Many viewed regenerative agriculture as a whole systems approach that values human health and community along with biodiversity and soil health. One retired farmer thinks of regenerative farming as a form of estate planning… setting up the land to be able to support the next generation. All the regenerative farms interviewed had similar farming ideals and practices for encouraging biodiversity and soil health, but the same cannot be said of their data collection and storage methods.

4.1.2. Current Record Keeping

Four main formats of data collection were used by the farmers: memory, handwritten paper notes, electronic spreadsheets or pdf documents, and Farm Management Information Systems (FMIS). Most farms applied a combination of these methods, with none storing all their records in one system. Half of the farms primarily used memory and handwritten notes, while the other half kept most records on spreadsheets and computer documents in the Google suite. The farms using Google Sheets spreadsheets were in the early stages of implementing FMIS and GIS programs.

The farms relying on worker memory and handwritten notes were generally older and kept less detailed records. The handwritten notes were relatively simple where one piece of paper would record the date, the general location, and the family of the crops being planted (Figure 15(a)). Similarly, Figure 15 (b) shows another handwritten note documenting harvests with the date, the general location, and the name of the crop being harvested. The planting locations were recorded as alphanumeric codes and, in some cases, had no physical map associated with them. The planting areas and subplots were instead held in the memory of farm workers and owners.



a. Planting Records b. Harvest Records

Figure 15. Images of hand-written planting (a) and harvest (b) records from a regenerative farm in Ventura County.

The farms with larger operations primarily used electronic spreadsheets (e.g., Google sheets) to manage their farm records. The details and complexity of the spreadsheets varied but they represented data from most farm departments including pasture, compost, garden records, and more (Figure 16). All the attribute data for these departments (e.g., crop disease and pest pressure, harvest quality, nutritional spray dates, animal grazing, compost temperatures etc.) were recorded in the respective spreadsheet and could only be accessed by viewing that spreadsheet.

	A	B	C	D
1	PastureMaster2018	1	2	3
2	Composting	11/14/2017 3 scoops	4/23/18 2 scoops	11/14/2017 3 scoops
3	2018-58 scoops tota	11/26/2018 2 scoops	11/26/2018 2 scoops	11/26/2018 2 scoops
4	Seeding	11/15/2017 2017 mix, bromes, radish, turnip	9/21/2017 2017 mix, bromes, radish, turnip	11/15/2017 2017 mix, bromes, radish, turnip
5		4/16/18 2018 pasture mix, cow pea, pearl millet, teff	4/23/18 2018 pasture mix, cowpea, pearl millet, teff	4/23/18 2018 pasture mix, cowpea, pearl millet, teff
6		5/31/2018 (teff, cowpea, pasture mix, pearl millet, bu	5/31/2018 (teff, cowpea, pasture mix, pearl millet, buckwheat)	
7		8/20/2018 sudex/cowpea/buckwheat (spot repair)	8/20/2018 sudex/cowpea/buckwheat spot repairs	8/20/2018 sudex/cowpea/buckwheat spot repairs
8		11/27/2018 oats/barley/field pea (35lbs) triticale (35 l	11/27/2018 oats/barley/field pea (30lbs) tricticale (30	11/27/2018 oats/ barley/ field pea (30lbs) triticale (30
9	Mowing	4/16/2018	4/23/2018	4/23/2018
10		5/29/2018	no mow (compare to pasture 1)	
11				
12				
13	Grazing	XXXXXX	4/16/18-4/17/18	4/18/18-4/19/18
14				
15		5/27/2018-5/28/2018 cows	5/29/2018-5/30/2018 cows	5/31/2018-6/1/2018 cows
16		7/17/2018-7/20/2016 cows following	7/19/2018-7/21/2018	7/22/2018-7/24/2018
17		9/18/2018-9/20/2018 11 cows	9/20/2018-9/21/2018 11 cows	9/21/2018-9/24/2018
18		11/18/2018-11/20/2018	11/20/2018- 11/21/2018	11/21/2018-11/24/2018
19				
20	Weeding	1/3/2018	1/3/2018	1/3/2018
21		3/8/2018	3/8/2018	3/8/2018

a. Pasture Records

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	VermicompostUsed												
2	Tea									Market			
3	Started Brew	Date Used	Tank	Origin	Amount (Gallons)	Area Treated	ection, grounds	Notes		Date bagged	Origin	Amount (quarts)	Notes
4													
5													
6													
7	?	6/26	B	V165	20	Avocados	injection	ɲjected at new well		7/8/20	V165	4	fm
8	6/10/20	6/11	A	V163	20			sprays		6/30/20	V165	4	fm
9	6/5/20	6/8	B	V163	20	M block/Garden	all			6/23/20	V165	18	fm
10	6/3/20	6/5	A	V163	20					6/19/20	V165	8	fm
11	6/2/20	6/4	B	V163	20	len,sprays,landscape				6/12/20	V165	12	fm
12	5/19/20	5/21,22,23	B	V162	20	avos, M	all	avos, sprays earlier in week		6/5/20	V164	10	fm
13	5/11/20	5/12-5/14-5/15	B	V162	20	?	all	ted pastures and avos		6/3/20	V164	12	fm
14	5/6/20	5/7/2020,5/8/20	A	V162	20		both	alf injected on pastures		5/29/20	V163	20	fm
15	5/1/20	5/4	B	V161	20	Mblock	injection			5/19/20	V162	13	fm

b. Compost Records

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Season	Island	General				Planning							Greenh
2			Crop	Variety	Planned Planting date	Bed #	Bed ft.	# of Rows	Total Row ft.	Spacing per Plant (in)	Plants per ft.	Total Plants Needed per Bed		Total GH Starter Plants Needed
9	Winter '20	A	Mixed Green	Yankee Blend	12/24	A7	78	6	468	0.5	24	11232		13478.4
10	Winter '20	A	Mixed Green	MR Salad blen	12/24	A8	35	6	210	0.5	24	5040		6048
11	Winter '20	A	Sage	Berggarten		A9	27	2	54	16	0.75	40.5		48.6
12														
13	Winter '20	B	Leeks	Tadorna	11/5	B1	42	3	126	4	3	378		453.6
14	Winter '20	B	Leeks	Tadorna	11/5	B2	54	3	162	4	3	486		583.2
15	Winter '20	B	Leeks	Tadorna	11/5	B3	60	3	180	4	3	540		648

c. Garden Records

Figure 16. Portions of spreadsheets used to track pasture (a), compost (b), and garden (c) records on a regenerative farm in Ventura County.

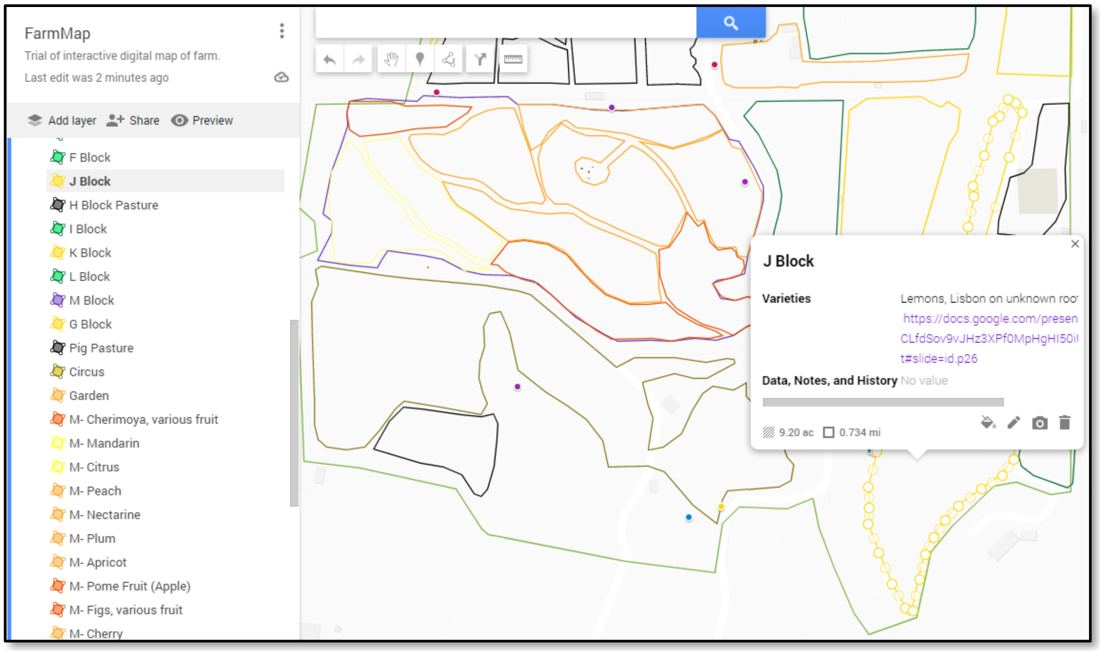
A majority of location information was stored as alphanumeric codes in the spreadsheets. These codes corresponded to locations on the farm which were noted on some type of map. One farm used a computer-drawn image of the garden bed shapes (Figure 17 (a)) and an aerial photo of the property (Figure 17 (b)) as spatial references for the codes. Because of the diversity of the farm operations, these regenerative farms recorded a variety of data without a uniform, systematic storage approach. Often, each department within a farm (e.g., compost, garden) had its own mixed system, with some records stored on paper, some in digital spreadsheets, and some in a FMIS or GIS. A positive development is that several of the farms interviewed had recently transitioned some records from mental and paper notes to digital spreadsheets, and some had even started to integrate FMIS and GIS programs into their records.

a. Computer-drawn garden beds

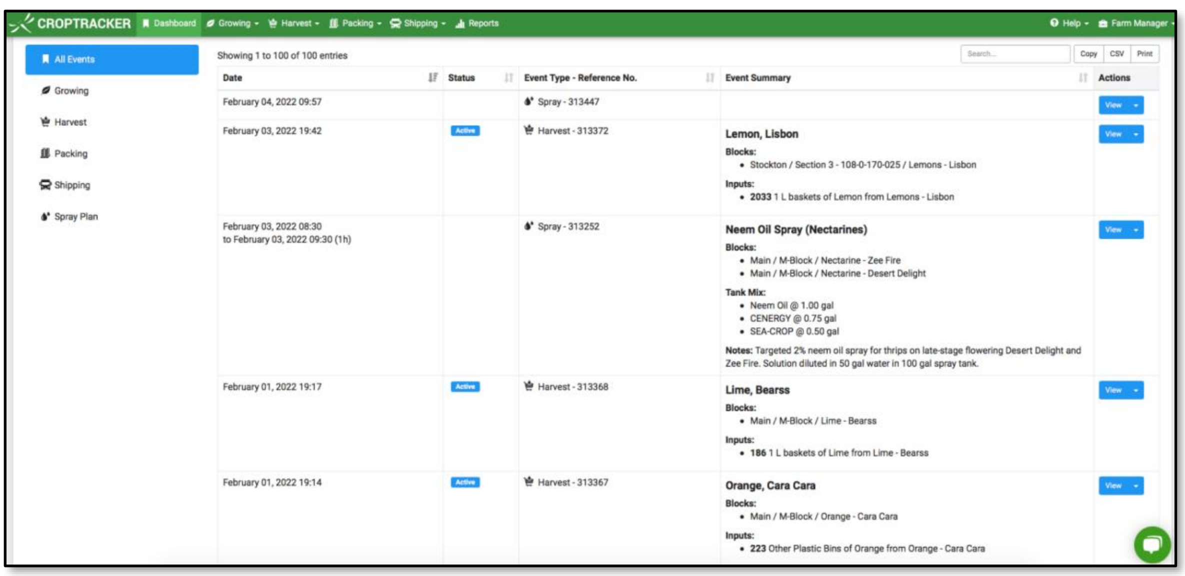
b. Aerial photo with labels

Figure 17. Physical hardcopies of farm locational references using (a) computer-drawn garden beds and (b) printed aerial photo imagery.

Farms that were comfortable using spreadsheets were experimenting with more advanced FMIS and GIS programs for their data management. These farms kept a subset of their records on programs including Google MyMaps, CropTracker, and ArcGIS Pro. Google MyMaps is a simple GIS program that can be used to create and display point, line, and polygon features representing farm entities. Each entity had a URL link to an online spreadsheet with attribute information about that entity. The computational limitations (e.g., a limit of ten layers per map), however, prevent MyMaps from scaling up to managing an entire farm's records. The same farm that used MyMaps also tested Crop Tracker, an online FMIS. Crop Tracker was able to meet some of the farmers' needs but had a difficult user interface and did not include any animal records. Figure 18 shows the user interface and some of the data stored in MyMaps and Crop Tracker from the farms interviewed.



a. A farm's location records on Google MyMaps.



b. A farm's records using CropTracker

Figure 18. Examples of farm records stored in (a) Google MyMaps and (b) CropTracker.

Another farm was in an early stage of adopting a more advanced GIS, ArcGIS Pro. This research-oriented farm had a 3rd party ESRI consultant and planned to use ArcGIS Pro for storing and analyzing data that contributes to the wider agricultural research community. Both farms using ArcGIS Pro and Crop Tracker had paid subscriptions to the software and collected geospatial data through a combination of digitizing over imagery, GNSS receivers, and iPhoto location data.

4.1.3. Farmer's Data Needs

The interviewed regenerative farms were varied in their record keeping styles and had different outlooks on their data needs. While the complexity of record keeping varied, all essentially boiled down to recording a timeline of practices and observations before and after planting. Based on the limitations of the farms' current systems, the farms were able to record and access this type of data in various degrees. While some farms kept minimal planting records, just enough to pass their certifications (e.g., "Organic", "Certified Humane"), some farms kept more detailed planting / treatment / harvest records, including the quality and performance of crops, the severity of pest and disease pressures, foliar spray and treatment schedules, timing of sap tests, bloom times, harvesting and watering amounts, equipment used, agronomy records, block observations, plant family succession records, and more.

Overall, the farmers wanted complete records of their farm to analyze their data and inform their farming practices and decision making. While some farmers were content with their current record keeping systems, they all acknowledged limitations that prevented them from easily storing and effectively accessing farm data. The farms using hand-written records were generating new planting/harvest pages daily, so the records quickly piled up and became difficult to organize and reference. The farms using digital spreadsheets and early FMIS struggled to keep track of the timing and history of targeted foliar sprays. Some farmers also wanted simpler data entry and were bothered by many unnecessary fields in FMIS and spreadsheets that complicated their data input and retrieval. Another common issue reported by the farmers was that record systems were still being developed, so the records needed to be stored across multiple platforms. These difficulties lead to poor accessibility (or nonexistence) of past records which was exacerbated by the relatively high turnover of farm employees.

4.2. Final Database Design and Implementation

The final ERD design was created with the needs of regenerative farmers in mind. The finalized ERD is described below, followed by a summary of the normalized farm data. Next the final physical database is created along with metadata describing the database attributes. The full code, queries, and data used for this database are stored in a GitHub repository and can be found at https://github.com/PhilipTHess/FarmDB.git.

4.2.1. Final ERD

The final ERD described below is an updated version of the ERD from Section 3.3.2. It was revised based on the interview results to better meet farmers' needs. The farmers wanted to track pest and disease pressures, general observations, harvest quantities and qualities, bloom times, and applications of fertility materials. They also expressed a desire for fewer and less complicated data tables and fields. The biggest changes made to the ERD involved standardizing data types, narrowing the database's focus to only agricultural records (rather than including personnel and infrastructure records), and condensing the data from each department into fewer tables with more useful attributes. The final ERD showing the logical schema of the database is illustrated in Figure 19.

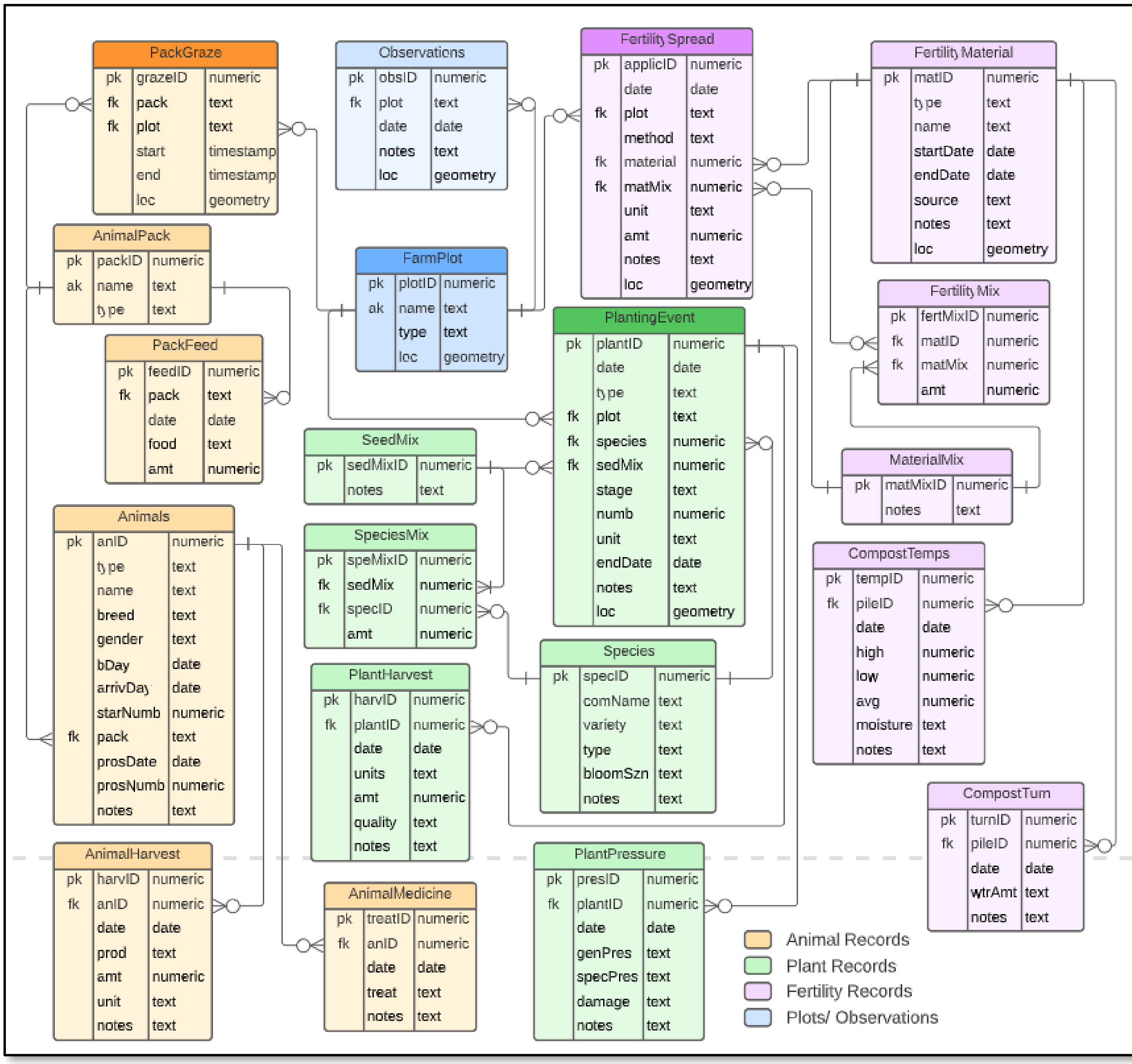


Figure 19. The final ERD showing the logical schema of a spatial database for a regenerative farm. General type of records are grouped by color.

As a spatial database, this database was organized around land area. The FarmPlot table holds polygons representing the farm's land areas, and everything recorded on the farm can relate back to these spatial entities. The Observations table records the date and location of any miscellaneous note or observation that warrants recording. PackGraze, PlantingEvent, and

FertilitySpread are the three other tables that relate to the FarmPlot table, and each of them connects to a group of farm records about animals, plants, and fertility respectively.

The PackGraze table connects the animal records to other farm data by describing which FarmPlot the animals have been in. An AnimalPack can be made up of many individual Animals (which is the smallest unit of record for animals, and it may for example represent one cow, or a shipment of 50 chickens). The "type" attribute of the Animals table tells the general species of the animal (such as chicken, cow, sheep, or bee). An AnimalPack can either graze (through the PackGraze table) or be fed supplemental feed (through the PackFeed table). Animals can be given medicine or specialized treatment (through the AnimalMedicine table), and they can be harvested or processed (including milk, egg, and honey collection or meat processing) through the AnimalHarvest table. As far as the relationships present in the animal portion of the database, one FarmPlot can contain zero to many PackGraze events. One AnimalPack can have one to many Animals in it and do zero to many PackGraze and PackFeed events. Animals can have zero to many AnimalMedicine treatment and AnimalHarvest events. The animal data have a similar relationship to the farm plots as the plant data.

The PlantingEvent table relates orchard, garden, pasture, habitat, and all other plant records to the FarmPlot table. Planting events involve a Species (the base unit of plant records) and describe when and where the planting occurred, how many individuals were planted, and when they were removed or died. Species can be combined in a mixture through the SpeciesMix table, and that mixture can be created and named by the SeedMix table which can be planted directly in a PlantingEvent. These two tables are necessary to avoid creating ambiguity in the relational database stemming from a many-to-many relationship. The "type" attribute classifies the purpose of the PlantingEvent (either for the garden, orchards, pasture, or habitat).

Information about the amount and quality of harvests, as well as pest and disease notes for each planting event can be stored in the PlantHarvest and PlantPressure tables, respectively. One FarmPlot can contain zero to many PlantingEvent records. One Species can be represented in zero to many PlantingEvent records, and one PlantingEvent can relate to zero or many PlantHarvest and PlantPressure records. One Species can also be in zero or many SpeciesMix; one SeedMix can be in zero to many PlantingEvents and can relate to one or many SpeciesMix records. Besides plants and animals, another main source of data generated by farms is related to fertility treatments that counter both nutritional deficiencies and pest and disease pressures.

Fertility data relates to the rest of the farm through the FertilitySpread table which describes applications of all kinds of materials (compost, pesticides, amendments etc.) referenced to which FarmPlot on which it is spread. Basic information about these materials is stored in the FertilityMaterial table including the name, source, type, and arrival date of the material. Similarly to Species and SeedMix in a PlantingEvent, FertilityMaterial can be spread individually or be combined in a mixture and spread together. Both the FertilityMix and MaterialMix tables are used to create a mixture and are required by the database to deal with an ambiguous many-to-many relationship. The FertilityMix table holds the materials (FertilityMaterial) in a mixture while the MaterialMix table creates and names the mixture so it can be spread (FertilitySpread).

There are two more tables of fertility records that store detailed information and notes about compost piles. The CompostTurn table records the building, turning, and watering of a pile and the CompostTemps table records the pile’s temperature changes. One FarmPlot can have zero or many FertilitySpread events and one FertilityMaterial can be spread zero or many times. One FertilityMaterial can correspond to zero or many CompostTemps or CompostTurn records and can also be in zero or many FertilityMix records. One MaterialMix name corresponds to one or many FertilityMix records and can relate to zero or many FertilitySpread records.

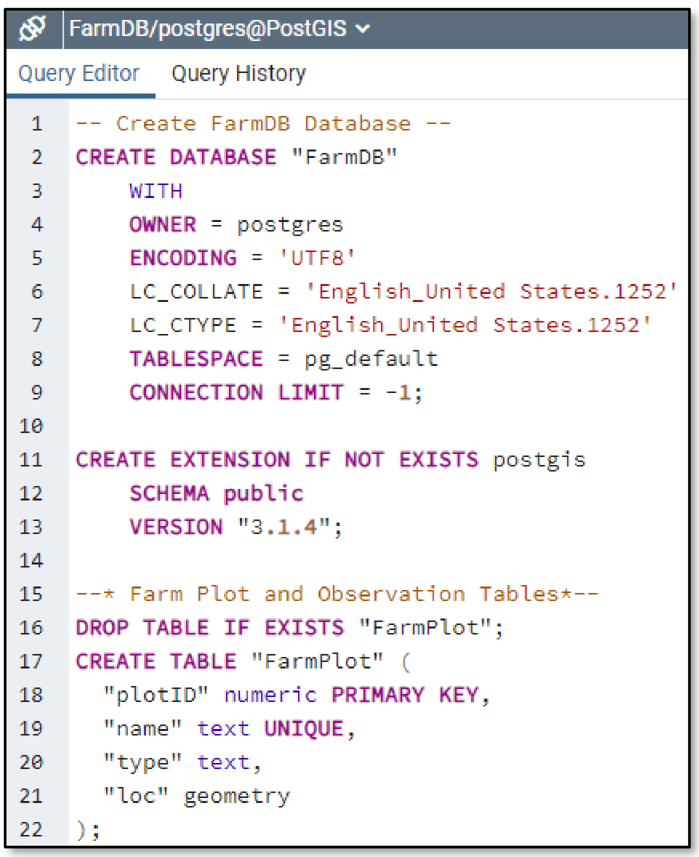
4.2.2. Farm Data

The raw data obtained from the farms (such as those in Figure 15, 16, 17, and 18) were organized, converted, supplemented, and normalized to the structure of the desired database tables. This demonstration database is designed to meet the record keeping needs of a diverse regenerative farm. The database is based on aggregated existing farm records and describes three years of records for a roughly 350-acre-sized farm. The farm consisted of ten animal pastures, five garden beds, five orchard blocks, five habitat zones, and five animal holding areas. There were two cow herds, two chicken coops, and six beehives which grazed the various farm plots throughout the years. The cow herds and chicken coops were made up of numerous animals and were regularly fed supplemental feed. Most animals were given some and possibly recurring medical treatments and were harvested either for meat or for by products (such as eggs, honey, or milk). The farm plots were planted with any one of the plant species, including multiple species at once. Some plantings had disease and pest notes, and some were harvested. Twelve compost piles as well as other pesticides and fertilizers were among the fertility materials spread on farm plots throughout the three years. These fertility materials were applied singularly and in combination, and each of the compost piles had regular turning and temperature notes.

The test data described above was aggregated from multiple farms, edited, and supplemented. It represents a demonstration database that could suit any regenerative farm's needs, it would just need to be populated with that farm's own data. Once interpreted and organized, these farm records were added to the database for easy retrieval and analysis.

4.2.3. Physical Implementation and Metadata

The database was coded using SQL based on the ERD outlined in 4.2.1. CREATE was the main function used to make both the database itself, and all the tables in the database. For every table created each of its attributes were also named and assigned data types. Primary keys, and foreign key constraints were added to the tables to enforce their relationship integrity. These constraints ensure that the data entered will be comparable throughout the database, and they define the connections between tables. Figure 20 shows the SQL scripts for the database creation, the addition of the PostGIS extension, and the creation of database tables. A full text version of the SQL creation scripts can be found in Appendix D.



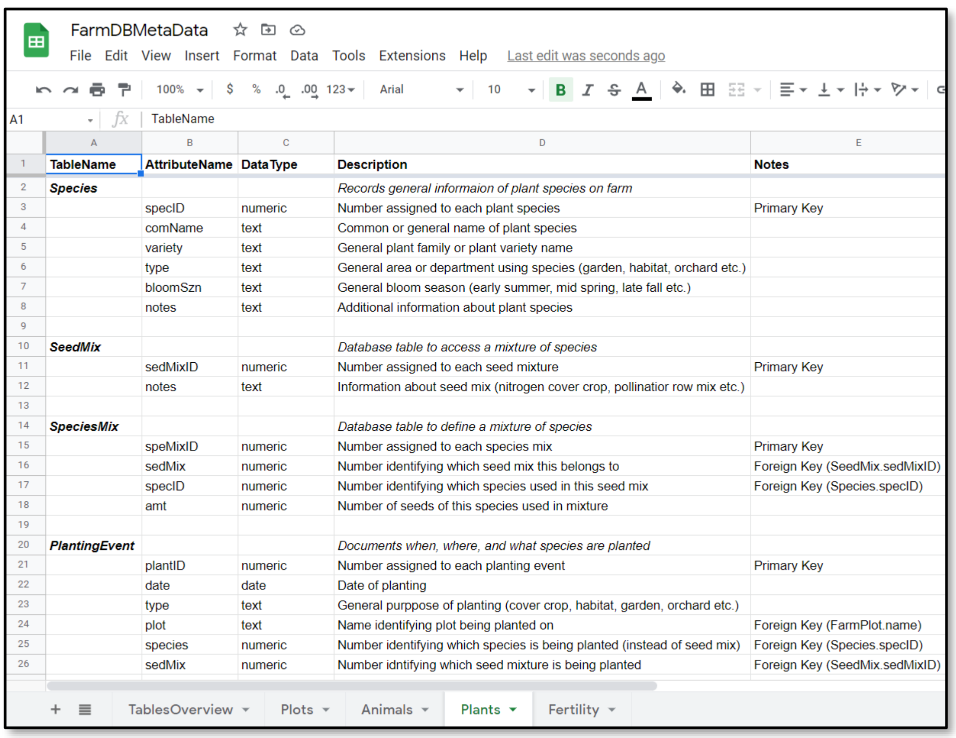

```sql
-- Create FarmDB Database --
CREATE DATABASE "FarmDB"
    WITH
    OWNER = postgres
    ENCODING = 'UTF8'
    LC_COLLATE = 'English_United States.1252'
    LC_CTYPE = 'English_United States.1252'
    TABLESPACE = pg_default
    CONNECTION LIMIT = -1;

CREATE EXTENSION IF NOT EXISTS postgis
    SCHEMA public
    VERSION "3.1.4";

--* Farm Plot and Observation Tables*--
DROP TABLE IF EXISTS "FarmPlot";
CREATE TABLE "FarmPlot" (
  "plotID" numeric PRIMARY KEY,
  "name" text UNIQUE,
  "type" text,
  "loc" geometry
);
```

Figure 20. A Screenshot of SQL used in pgAdmin 4 interface to create a farm database, add the PostGIS extension, and create database tables.

A database is only useful if people understand what data it is meant to hold. For this reason, as soon as a table was added into the database, its metadata was documented to describe what that table and its attributes represented. For this database, the metadata was entered as a Microsoft Excel spreadsheet, saved as a .csv text file, and included as a table in the database itself for easy reference. This metadata lists every table in the database, describes its purpose, and notes every attribute including a description of what information should be stored in that field as well as its data type. Relationships were described in the metadata so that it is clear how to join tables and when it is appropriate to do so. Figure 21 shows an example of these metadata spreadsheets. The full metadata of attribute descriptions can be found in Appendix E.



TableName	AttributeName	DataType	Description	Notes
Species			*Records general informaion of plant species on farm*	
	specID	numeric	Number assigned to each plant species	Primary Key
	comName	text	Common or general name of plant species	
	variety	text	General plant family or plant variety name	
	type	text	General area or department using species (garden, habitat, orchard etc.)	
	bloomSzn	text	General bloom season (early summer, mid spring, late fall etc.)	
	notes	text	Additional information about plant species	
SeedMix			*Database table to access a mixture of species*	
	sedMixID	numeric	Number assigned to each seed mixture	Primary Key
	notes	text	Information about seed mix (nitrogen cover crop, pollinatior row mix etc.)	
SpeciesMix			*Database table to define a mixture of species*	
	speMixID	numeric	Number assigned to each species mix	Primary Key
	sedMix	numeric	Number identifying which seed mix this belongs to	Foreign Key (SeedMix.sedMixID)
	specID	numeric	Number identifying which species used in this seed mix	Foreign Key (Species.specID)
	amt	numeric	Number of seeds of this species used in mixture	
PlantingEvent			*Documents when, where, and what species are planted*	
	plantID	numeric	Number assigned to each planting event	Primary Key
	date	date	Date of planting	
	type	text	General purppose of planting (cover crop, habitat, garden, orchard etc.)	
	plot	text	Name identifying plot being planted on	Foreign Key (FarmPlot.name)
	species	numeric	Number identifying which species is being planted (instead of seed mix)	Foreign Key (Species.specID)
	sedMix	numeric	Number idntifying which seed mixture is being planted	Foreign Key (SeedMix.sedMixID)

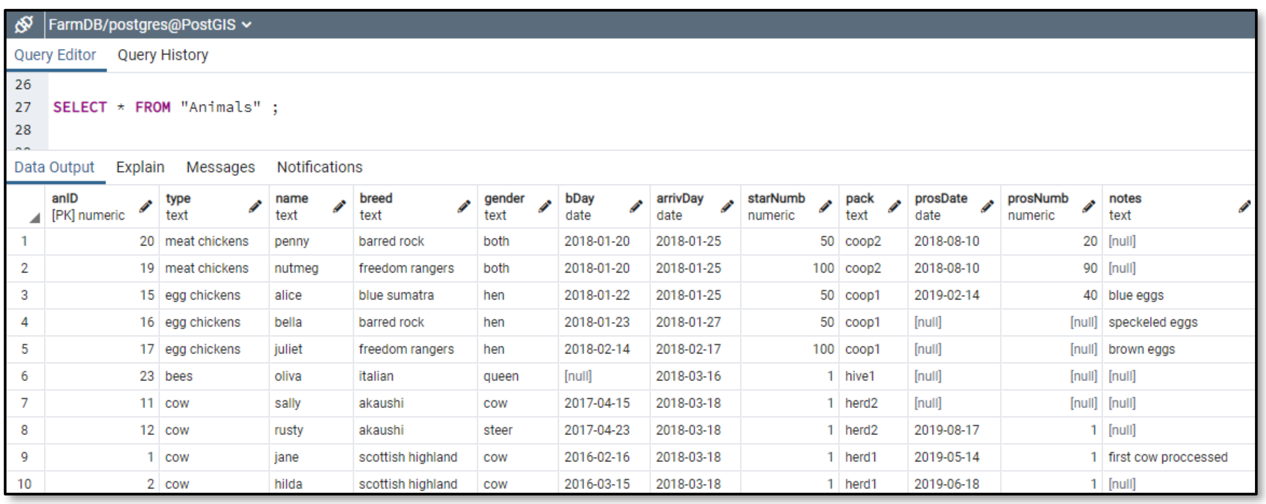
Figure 21. A spreadsheet of metadata describing the database tables, attributes, and relationships.

4.3. Data Queries and Visualization

This section focuses on retrieving the farm data from the database through four types of SQL queries: simple, relational, temporal, and spatial queries. The syntax of all queries in this section were demonstrated in the top half of each associated figure under "query editor"; the text format of these queries can be found in Appendix F.

4.3.1. Simple Database Queries

Figure 22 shows an example SQL query that accesses the data stored in one single table 'Animals'. An asterisk (*) in the SELECT statement selects all the columns in the table as the output. The resulting table in the lower half of Figure 22 displays this output of all columns in the Animals table. This simple query (Query 1) can be applied to any table for retrieving all the data stored in the table effectively.


FarmDB/postgres@PostGIS

Query Editor   Query History

```
SELECT * FROM "Animals" ;
```

Data Output   Explain   Messages   Notifications

	anID [PK] numeric	type text	name text	breed text	gender text	bDay date	arrivDay date	starNumb numeric	pack text	prosDate date	prosNumb numeric	notes text
1	20	meat chickens	penny	barred rock	both	2018-01-20	2018-01-25	50	coop2	2018-08-10	20	[null]
2	19	meat chickens	nutmeg	freedom rangers	both	2018-01-20	2018-01-25	100	coop2	2018-08-10	90	[null]
3	15	egg chickens	alice	blue sumatra	hen	2018-01-22	2018-01-25	50	coop1	2019-02-14	40	blue eggs
4	16	egg chickens	bella	barred rock	hen	2018-01-23	2018-01-27	50	coop1	[null]	[null]	speckeled eggs
5	17	egg chickens	juliet	freedom rangers	hen	2018-02-14	2018-02-17	100	coop1	[null]	[null]	brown eggs
6	23	bees	oliva	italian	queen	[null]	2018-03-16	1	hive1	[null]	[null]	[null]
7	11	cow	sally	akaushi	cow	2017-04-15	2018-03-18	1	herd2	[null]	[null]	[null]
8	12	cow	rusty	akaushi	steer	2017-04-23	2018-03-18	1	herd2	2019-08-17	1	[null]
9	1	cow	jane	scottish highland	cow	2016-02-16	2018-03-18	1	herd1	2019-05-14	1	first cow proccessed
10	2	cow	hilda	scottish highland	cow	2016-03-15	2018-03-18	1	herd1	2019-06-18	1	[null]

Figure 22. Simple query (Query 1) with a portion of its data output. Query 1 retrieves all records from the Animals table.

If a farmer is interested in only certain records in the Animal table, the SQL query can filter the data by specifying the columns desired within a table. Figure 23 shows a query (Query 2) to only display the type, name, and breed of the Animals table.

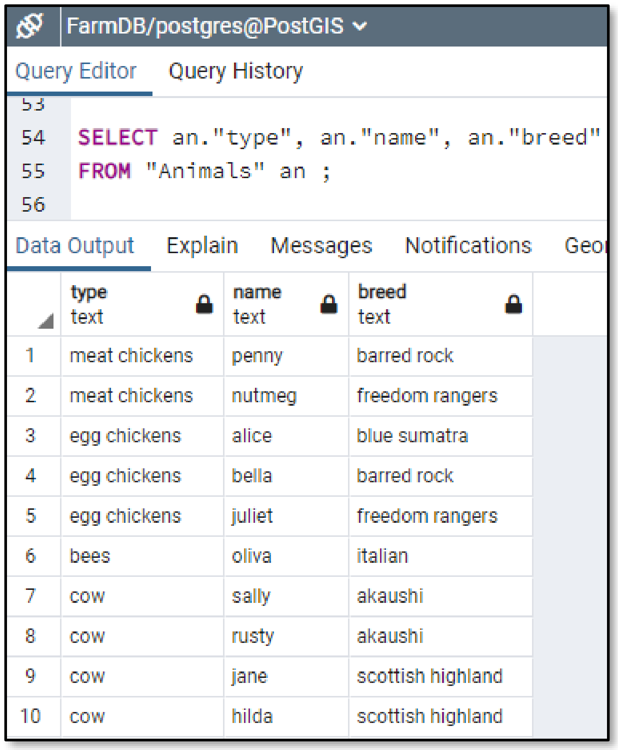


Figure 23. Simple query (Query 2) with a portion of its data output. Query 2 retrieves certain columns from the Animals table.

To further narrow down a single data table, Figure 24 shows a SQL query (Query 3) that displays certain records from animals that are cows (therefore excluding all chicken and bee records) by using the WHERE clause (i.e., WHERE an.type = ‘cow’).

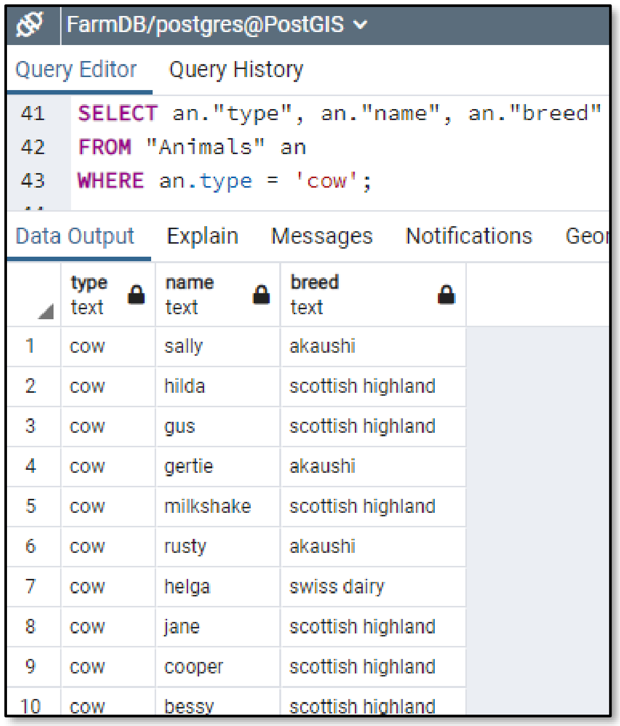
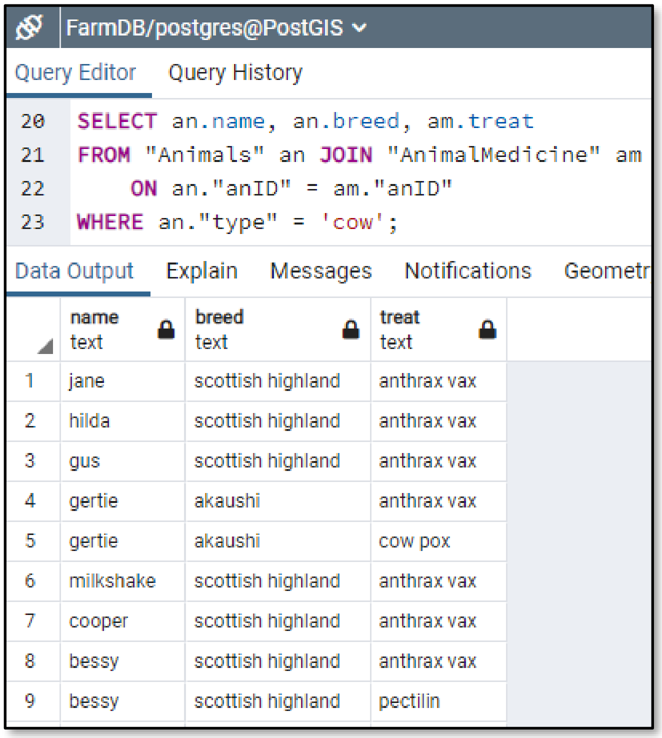


Figure 24. Simple query (Query 3) with a portion of its data output. Query 3 retrieves specific columns from the Animals table that represent cows.

The examples presented in this subsection are relatively simple but can be much more complex if needed. Other logical operators (e.g., AND, OR) and aggregate functions (e.g., COUNT, SUM) can further customize the data query output, and multiple functions and tables can be combined into a single query.

4.3.2. Relational Queries

Relational queries utilize the JOIN function to retrieve data records from different tables in the database. Such queries increase the efficiency of data access. For example, if a farmer wanted to know what treatments they have given to each of their cows in the AnimalMedicine table, but there was no animal type information stored in the AnimalMedicine table, a solution is to join the Animals and AnimalMedicine tables. Figure 25 shows an example SQL query (Query 4) that finds all the columns from the Animals table that are cows, then matches the common key "anID" (which is an ID number for each animal) between the animal table Animals and the treatment table AnimalMedicine. The query temporarily combines and displays only the relevant data. In this case, the query shows what treatments were given to cows, what those cows' names were, and their breed.




```sql
SELECT an.name, an.breed, am.treat
FROM "Animals" an JOIN "AnimalMedicine" am
    ON an."anID" = am."anID"
WHERE an."type" = 'cow';
```

	name text	breed text	treat text
1	jane	scottish highland	anthrax vax
2	hilda	scottish highland	anthrax vax
3	gus	scottish highland	anthrax vax
4	gertie	akaushi	anthrax vax
5	gertie	akaushi	cow pox
6	milkshake	scottish highland	anthrax vax
7	cooper	scottish highland	anthrax vax
8	bessy	scottish highland	anthrax vax
9	bessy	scottish highland	pectilin

Figure 25. Relational query (Query 4) with a portion of its data output. Query 4 retrieves name, breed, and medical treatments of all cows.

4.3.3. Temporal Queries

Temporal queries are used to connect and track data through time. In this database, they are possible because of the "date" and "timestamp" data types. As mentioned in Section 3.3.3, date and timestamp represent actual dates on the calendar. The database can recognize the relationships between dates or timestamps, such as if one date is before or after another, how long between two dates, and more. Temporal queries can be particularly effective at filtering through data once there are years of accumulated records. Figure 26 shows an example SQL query (Query 5) that focused on a specific time period of records. In this example, the query retrieved the varieties, common names, and planting dates of all garden crops that were planted in the first two months of 2018 (i.e., BETWEEN ‘2018-01-01’ AND ‘2018-03-01’).

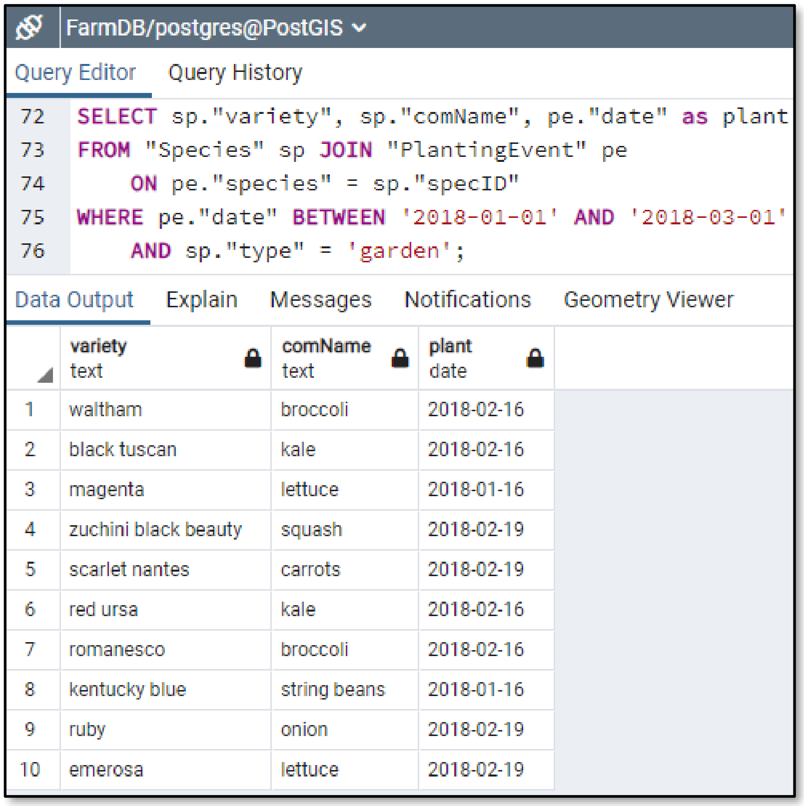
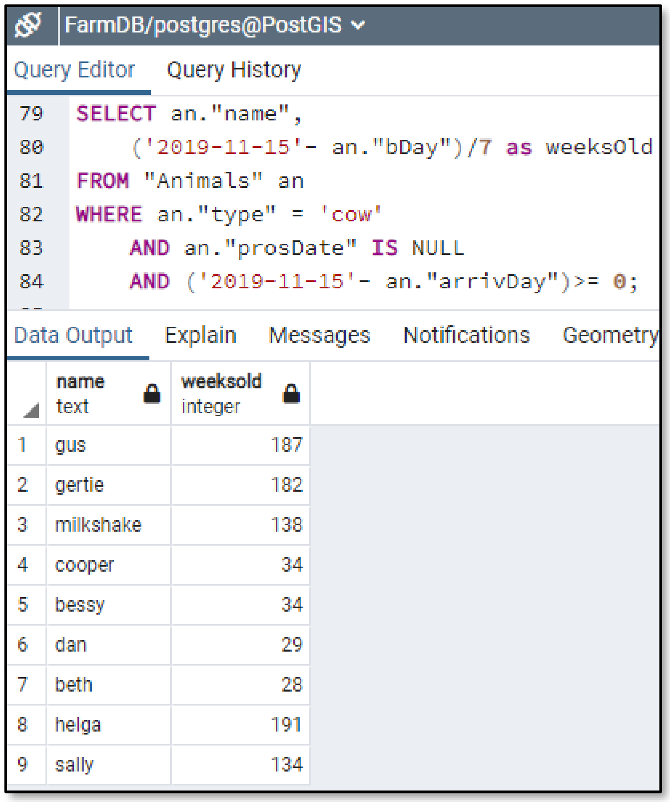


Figure 26. Temporal query (Query 5) with its data output. Query 5 retrieves variety, common name, and plant date of garden crops planted in the first 2 months of 2018.

Another use of temporal queries is to calculate the time between specific event dates. Figure 27 shows a query (Query 6) which calculates and displays the age of each cow (i.e., the time between the animal’s birth and the queried date).

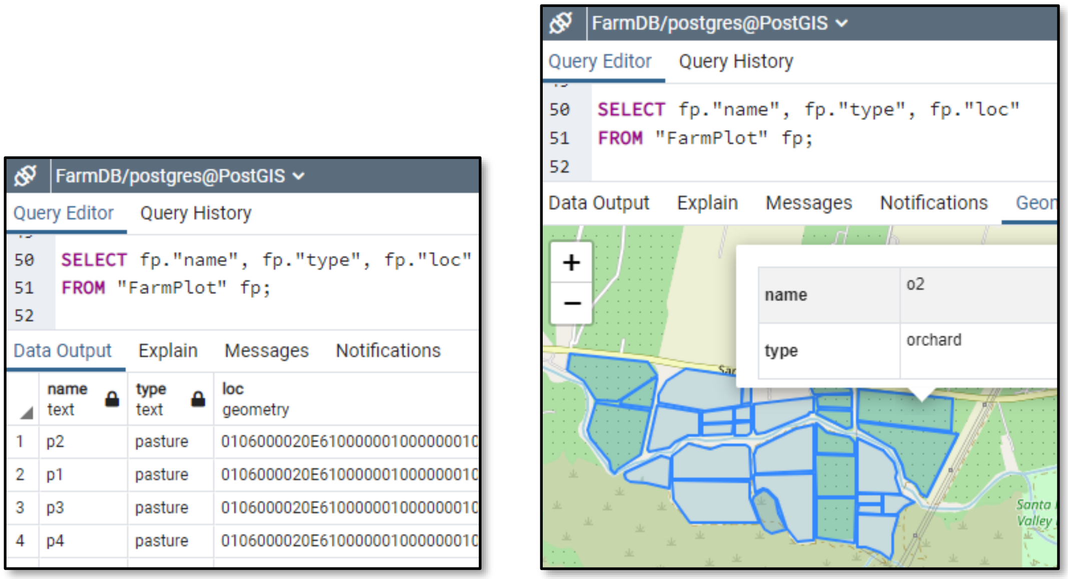


	name text	weeksold integer
1	gus	187
2	gertie	182
3	milkshake	138
4	cooper	34
5	bessy	34
6	dan	29
7	beth	28
8	helga	191
9	sally	134

Figure 27. Temporal query (Query 6) with resulting data output. Query 6 finds the age in weeks of all cows on farm (on Nov. 15, 2019).

4.3.4. Spatial Queries

Spatial queries use shared geometry between spatial entities for data retrieval. They are possible because of the "geometry" data type enabled by the PostGIS extension. Figure 28 shows a SQL query (Query 7) of a spatial entity "FarmPlot", the resulting table and the map view ("geometry viewer") of the data locations (a and b, respectively).



(a)

(b)

Figure 28. Spatial query (Query 7) with a portion of its data output (a) and map view (b). Query 7 shows name, type, and location of all farm plots.

Similarly to temporal queries, spatial queries can also apply mathematical functions. Figure 29 shows a spatial query (Query 8) that retrieves the area and perimeter of each farm plot while converting the units of area to acres. Spatial queries can be combined with relational and temporal queries. Figure 30 shows a query (Query 9) that finds the location and pack name of all the animal packs currently on the farm (for a given date- April 16, 2019). This could be useful to fertility workers collecting manure, the livestock team planning grazing routes, the pasture manager deciding on seeding time and more.

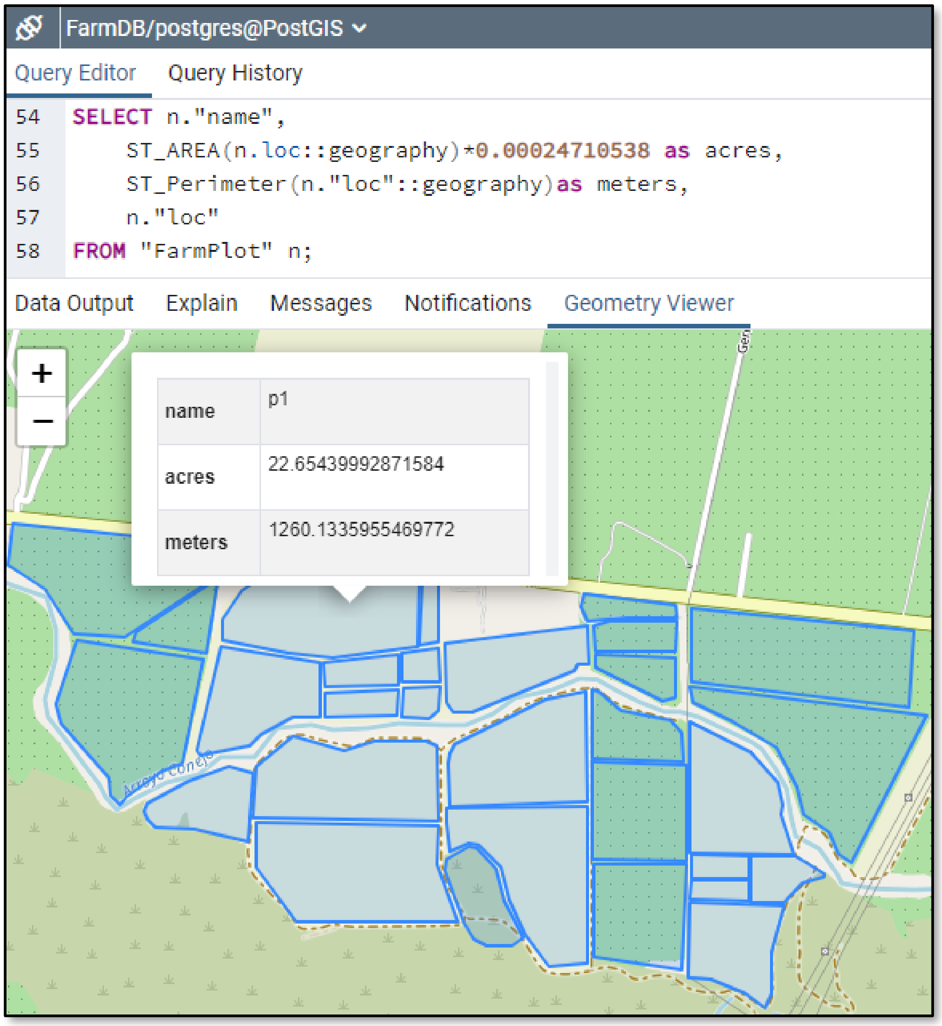


Figure 29. Spatial query (Query 8) with a portion of its geometry viewer output. Query 8 finds the area (in acres) and perimeter (in meters) of each farm plot.

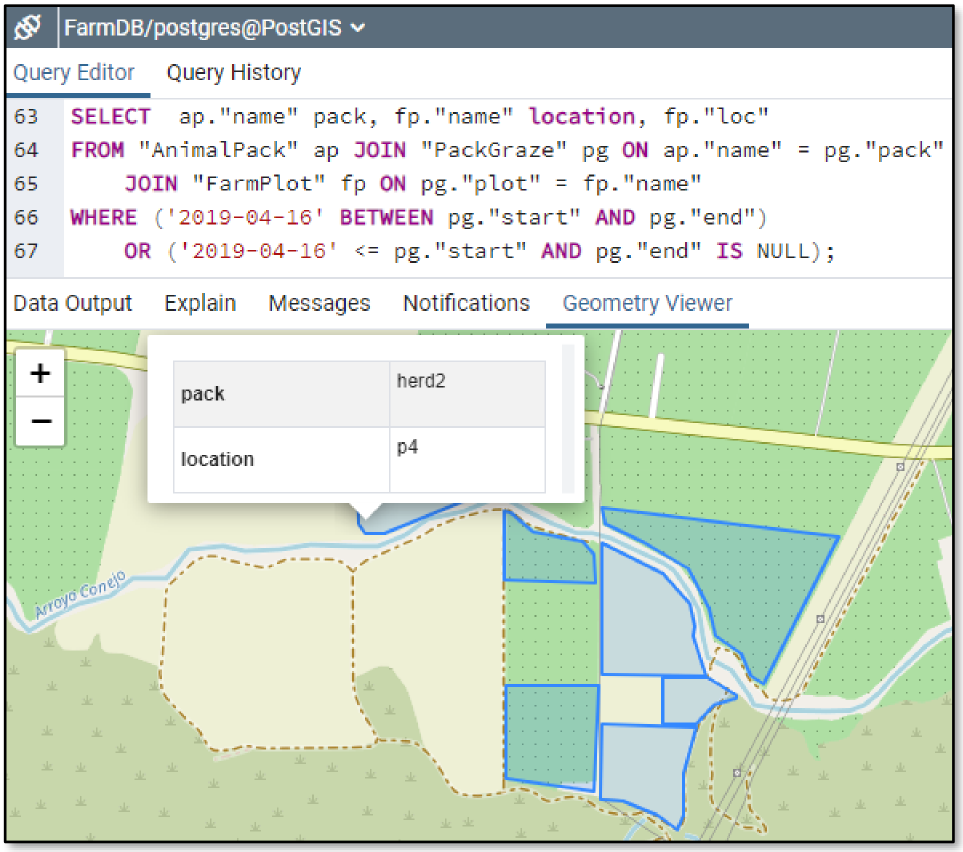


Figure 30. Spatial query (Query 9) with a portion of its geometry viewer output. Query 9 finds current location of animal packs (April 16, 2019).

The example SQL queries above demonstrate the retrieval and analysis of data between tables of one department, but spatial queries can also combine data from multiple departments at once (i.e., animals, plants, and fertility). The final example, Figure 31 shows a more complex spatiotemporal query(Query 10) that accesses data from every farm department and displays the results together. This query provides a summary of the farm in 2018 including the name and location of each FarmPlot, the total number of days it has been grazed by cows and by chickens, the amount of compost spread per acre, and the number of times planted that year.

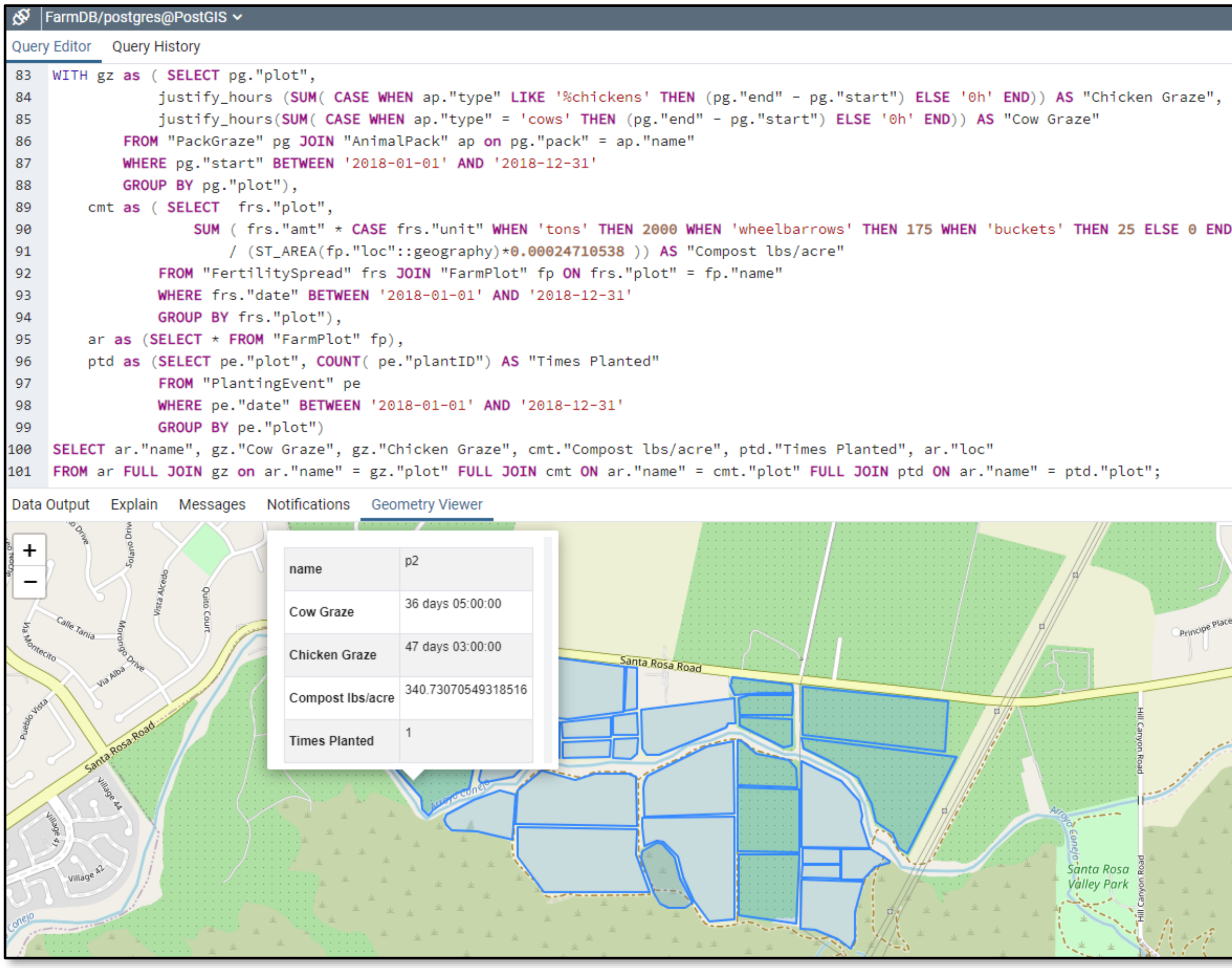


Figure 31. Spatial query Query 10) with a portion of its geometry viewer output. Query 10 displays a summary of each farm plot in 2018 including the name and location of the plot, the total number of days it has been grazed by cows and by chickens, the amount of compost spread per acre, and the number of times planted that year.

Chapter 5 Conclusion and Discussion

The objective of this thesis is to create a spatial database for agricultural record keeping designed to effectively utilize the spatial and temporal nature of agricultural data to support decision-making on a regenerative farm. The database accomplishes these goals but there is room for improvement. This final chapter presents some conclusions about the creation of this spatial database and its effectiveness for regenerative farmers (Section 5.1). It then identifies the database's limitations (Section 5.2) and concludes by discussing future directions (Section 5.3) that would make the database more valuable to farmers.

5.1. Conclusions

Farms are an integral part of society and have a long history of management and record keeping practices. Improvements in recork keeping, from spreadsheets to computer databases to GIS management systems are particularly worthwhile for regenerative farms which have many variables to keep track of in their diverse systems. The layered interaction between entities makes it more challenging to set up a data management system for a regenerative farm than for an industrial monoculture operation.

Spatial databases are an effective way for farmers to store, access, and analyze their data but face barriers to adoption based on the technical expertise required to maintain the database. The spatial database created for this thesis stores spatial, temporal, and other attribute data representing entities and relationships relevant for record keeping and management of a regenerative farm. All this data can be combined, analyzed, and viewed using SQL queries. Accessing all a farm's data in one place was a common goal for farmers when asked about their data needs, and this database accomplished that goal. Though this research was developed for regenerative farms in Ventura County, the database and farming principles applied can be useful to farms anywhere in the world. This section elaborates on the conclusions of this research in terms of the effectiveness of the database, and its overall value to regenerative farmers.

5.1.1. Effectiveness of Database

Recent data from one table may be easy to access with a farm's previous record keeping methods, but querying a spatial database is more effective when combining data from multiple tables, departments, or time periods. Most spatiotemporal queries (such as the final query in Chapter 4) represent information that would be near impossible to reliably calculate without a spatial database. It would involve sorting through, calculating, and summarizing values from thousands of records and across various tables. Even if it were possible to calculate that information from previous record keeping methods, it would be prohibitively time consuming to replicate those calculations for all farm plots, and the process would have to restart to account for a different time period than the year 2018.

Alternatively, queries to this database are easily saved, copied, and edited, so they can be useful to a farm for a long time. Even a farmer who is not comfortable writing queries from scratch could make small tweaks to an existing query for newly customized results. As an example, any of the temporal queries from Chapter 4 can be changed to find information from a different time period simply by changing the dates that appear in the query text itself. In this way, one query can be edited and re-run to regularly provide valuable information to a farm throughout the years.

5.1.2. Overall Value

The most direct value of these systems comes from their ability to inform decision making. They allow farmers to answer questions with data. Even when storing limited amounts of records, a spatial database can be more effective than some current storage methods. Still, the more data that farms put into the database, the more value they can ultimately get out of it. A complete spatial database is particularly useful for farm research projects because of its ability to store and organize large amounts of historical records. These records can represent multiple farm departments and span numerous years. This database organization could also help facilitate the record retrieval required for certifications.

Ultimately, value comes from the ability to access, combine, and filter data in ways that open the door to new analyses and inform decision making. Queries do not have to be long and complex to be valuable for farmers. The following describes a few queries (drawing on those detailed in Chapter Four) and what specific farming decisions they could help inform:

- Finding the perimeter of a planned grazing area could inform how much fencing needs to be set up in the field.
- Grazing, seeding, and compost history could inform many farm decisions such as the timing and amounts of future animal grazing, and compost or seed spreading.
- Finding the current location of all animals can inform where to start harvesting or applying pesticides or compost (to make sure animals do not get in the way of the application or harvest).

These are only a few examples, but there are endless possible farm management insights that could come from regular use of a spatial database. Getting the most value out of the database would require some farmers to collect more frequent and detailed data, which is a factor in the system's overall value.

While many improvements in data access and analysis come from using a spatial database, the overall value that these systems bring is more nuanced and varies depending on the farm involved. Any kind of organizational system is only useful if it is used and maintained regularly. Those farms which employ this type of spatial database should be willing to upkeep the system, including inputting new data as it is generated. While there are many levels of database use that can be effective, forcing the use of a database will not bring positive results, and the database will only be valuable if farm workers and managers engage with it.

5.2. Limitations

This database has some limitations that hold back its effectiveness for farmers. The following section discusses some of this database's limitations including difficult data entry and output, some computational inefficiencies, and the fact that it is not currently optimized for a specific farm.

The main methods for data entry in this database involve filing out spreadsheets, digitizing satellite imagery, importing .csv and shapefiles, and using SQL to add them to existing tables, all of which can be tedious and are prone to error. These methods of data entry require some technical knowledge and involve working directly with the database software. Query results are the main form of data output from this database. While they can be very powerful, queries also require a certain level of technical proficiency to create, and those constructing the queries must be familiar with the database structure and relationships. This represents a steep learning curve for farmers using the database before they can effectively access and filter their data. The visual output is less than ideal because the graphical interface of pgAdmin is designed to build and maintain a database, not for complex data visualization or mapping. Along with the difficulties involved in data entry and output, this database also has a few computational inefficiencies that hinder its scalability.

This database was designed to be flexible and to fit many farmer's needs, but some of that flexibility comes at the cost of computational efficiency. One source of inefficiency comes from unnecessary fields. The notes fields were included in many tables so that it is easier for a farm to start using this database, essentially giving them an open column in most tables to record any extra information not accounted for in the table. Some of the tables have an alphanumeric code connecting them spatially as well as a geometry field. The alphanumeric code allows farmers to keep their data spatially referenced without needing to create a new polygon for every record. It is simple to use but less functional than including actual location in "geometry" data type. These gains in flexibility and user friendliness limit the computational efficiency of the database. Adding indexes (including spatial indexes) is an extra programing step but would improve the efficiency of relational queries. From a surplus of attribute fields to a lack of indexes, these processing inefficiencies are manageable while the database is small but will slow the system down as more data is added and records accumulate over time. The limitations discussed up to this point are all a reflection of the database not being designed and optimized for one specific farm.

The decisions behind its design and the data stored in the database were aggregated from multiple sources, thus this database represents only a theoretical farming operation. The 30-minute semi-structured interviews were effective but did not include the level of access that would be required to create a farm-specific custom database. Customization to that extent would require regular stakeholder input about the data volume expected, specific data needs, and more. Instead, the database was designed and populated as a model and demonstration of a spatial database for agricultural recordkeeping. The database was designed to be usable by any operation, but was not optimized to any specific one, which explains some of the limitations described earlier in this section. Addressing these limitations would improve the effectiveness of the current database. There are also several future directions and additions to the database that could provide new functionality and make the database more practical and integral to farm management.

5.3. Future Directions

Beyond the efficiency and optimization improvements discussed in the previous section, this database could be built on to expand its capabilities, improve its accessibility, and increase its overall value to farmers. While not within the scope of this paper, there are many directions that this database could grow to improve its usefulness to farmers. Some examples of these future directions include incorporating more sources of spatial data (such as GNSS and RS data), developing an application for easier user interface, and integrating the database with a certifying body to easily judge certification compliance.

Spatial queries connect data across all departments, even while utilizing just one table (FarmPlot) with spatial data. The more spatial data being held in the database, the more advanced the spatial queries can get. GNSS data is locational data from a satellite gathered at a particular receiver's location. GNSS receivers could be carried in the field to easily mark locations of animal fencing, pest problems, and more. RS data can come directly from sensors on satellites, aircraft, or drones. RS data can include multispectral imagery, lidar imagery, and more, all of which can give valuable insights into the land. Multispectral imagery can be used to analyze plant health, and lidar can create highly accurate elevation data. Both GNSS and RS data can be georeferenced and combined with other farm data in queries and visualizations.

While this thesis focuses on the Postgres, PostGIS, and pgAdmin interfaces, a spatial database can also be recognized by separate GIS programs (such as QGIS) for more advanced mapping outputs. These GIS programs would help display a more visually appealing graphical overlay of the data compared to the pgAdmin Geometry Viewer. A custom-built application could further address the database's data input and output limitations. This application should be designed with a simple user interface to improve farmers' interactions with their data. To maintain its functionality to farmers, the app should support complex, customizable queries. A mobile version of the app could allow data access and entry in the field, making it much more practical for daily use. Frequent use of the database (through the application) increases the amount of data coming into the system, which improves the database's analytical potential.

A spatial database like the one outlined in this thesis could document information needed for farm certifications. The certifying body could use preset queries to assess certification compliance, and such queries could be readily edited to reflect changing standards over time. Many regenerative farms focus on selling locally and directly to consumers. Including sales and customer records in the database would allow farmers to track their crops' life from planting to consumption and begin to quantify how local their food distribution is. This type of quantification could also help certifiers verify which farms are selling to local and direct markets (which could be a requirement for certification).

The database could also incorporate a higher level of organization where all the tables have a specific FarmID code. This would allow multiple farms to keep their data separated, but on the same database system. With the proper permission restrictions to preserve privacy, data could be aggregated across farms to assess more regional impacts of farming and food distribution. This type of system could have serious implications for certifiers, researchers, city planners, and more.

Given agriculture's widespread use and value to humans, improvements in agricultural management have the potential to impact everyone in the world. A spatial database can aid in farm management but is only useful to farmers if they use it. The database and organizational system proposed in this thesis would only be successful in the field with intentional development and the continuing support of both farm management and workers.

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Appendix A Social Behavioral IRB Protocol

Social Behavioral Protocol

Study Title: Spatial Databases for Diverse Agricultural Record Keeping

PI Name: Philip Hess

Study Procedures

1. Background/Rationale

Much research combining Geographic Information Systems (GIS) and agriculture is focused on expensive precision agriculture (PA) systems for large monoculture farms. While this is a valid use of the technology, GIS has often been overlooked by (but can still greatly benefit) small, diverse farms. Regenerative agriculture (which describes the aforementioned small diverse farms) involves many moving parts, all of which exist on the land— from crop placement and succession planting to livestock rotation, grazing patterns, and irrigation plans. These all have significant temporal and other attribute data associated with them and would be best organized with a spatial database.

Many studies and projects have the goal of improving agriculture, and they approach those improvements in various ways, from real time productivity analysis to national recordkeeping to GIS integration. This thesis will focus on agricultural spatial databases for individual farm management and recordkeeping on diverse farms as an area that needs development.

2. Purpose/Objectives/Aims/Research Questions

This thesis outlines the creation of a spatial database as a system of record keeping for a small diverse farm. It will involve research and interviews with experts in the field to design said database and assess its effectiveness compared to other record keeping methods.

3. Participants (sample)
    a.
    This study is interested in talking with farmers and researchers in Ventura County who practice regenerative agriculture (Polyculture farming under 500 acres). The farms will be selected from location-based internet searches (within Ventura County). I will use a regenerative agriculture website (RegenerationInternational.org) which documents the location of regenerative farms around the world, as well as google maps search for regenerative agriculture. I will also research any official certifying bodies for regenerative agriculture in Ventura County.

c. Participants are not part of a spatial subject population.

4. Recruitment/Screening Process (sampling strategy)

   The initial search results were narrowed down based on how diverse the farms are. Farms that only grew one type of crop will be removed from the study. For example, regenerationinternational.org showed 6 farms in Ventura County, but upon further investigation most of them did not meet the diversity requirement of this study. One produces only beef, one only pork, one only orchard trees, and one only produces vegetables. The Google Maps results require a similar screening process. An initial search of "regenerative agriculture in Ventura County" produced many results including agricultural service companies and farmers markets. I narrowed this down to only the businesses listed as "Farm" or "Education Center". I only found one Regenerative certification, and while it is still in its early development stages, two of its founding companies are based in Ventura County.

   Overall, I am hoping to identify 5 or 6 qualifying organizations in hopes that at least 3 will be available and willing to participate.

   Recruitment will take place via email to the companies involved. Appropriate consent will be shown in the email and verified in each interview. Interviews will take place over the phone. Site visits may be scheduled after the initial phone interview if needed to collect or verify data.

5. Methods
   a.

      I started with research on the many complexities of regenerative agriculture. I Specifically focused on efficient ways to keep records and store data. I am continuing that research by talking with local regenerative farmers and others in the regenerative agricultural community about their current record keeping systems, data analysis needs, and general farming practices. I will use this information to design a spatial database to hold agricultural records. I will also get copies of archival farm data from the organizations interviewed (in the form of spreadsheets, word processing documents, and handwritten notes). This data will be cleaned and edited to populate the newly created database. The database will be tested with queries that would be useful for day-to-day farm management. There will be follow up interviews to demonstrate the database and assess its effectiveness.

      i. Regenerative farms and leaders in the regenerative movement in Ventura County CA were contacted via email. They will be informed of the study, and be invited to be interviewed in said email. One representative from each organization will be interviewed over the phone for approximately 20 minutes based on the semi structured interview procedure attached to this application (istar application section 13) which includes requesting access or copies of archival farm records. Their consent will be verified over the phone during the interview. Site visits may be scheduled after the initial phone interview if needed to collect or verify any data.

Responses to interviews will be documented in notes by the interviewer. These notes will be used to develop a spatial database to hold records for diverse farms and assess if it meets their needs. Once the database is created, it will be populated with cleaned archival farm records. The database's usefulness will be demonstrated through queries and shown to farmers to get their reactions in a follow up interview (~2 months after initial interview).

The final results and conclusions will be prepared in a thesis paper and distributed through standard USC MS GIST theses.

iv.

A.

Notes will be identifiable by name of the organization being interviewed. Archival farm records may also be used to demonstrate the use of the database. This may include location data that could be linked to the address of the business.

v.

All data will be stored on the personal computer of the principal investigator. Eventually the archival database may be stored on ArcGIS Online, as a PostGIS database or in another database system per institutional policy.

vi.

This project involves writing and defending a Masters thesis paper. Findings and results will be disseminated through the standard methods of a USC GIST Masters Thesis.

b. Instrumentation

Questionnaires/Survey Measures (names and citations)

General exploratory interview questions were developed by the investigator. It is a semi-structured, open ended interview with questions such as "what information do you record about the crops you grow" and "what is most lacking about your current record keeping system?". The questions are designed to get an understanding of the current farming practices and record keeping systems on regenerative farms, and to explore how they can be improved. (see interview script Section 13 of istar application).

Qualitative instruments

Some qualitative questions will be introduced in this semi structured/ open ended interview process.

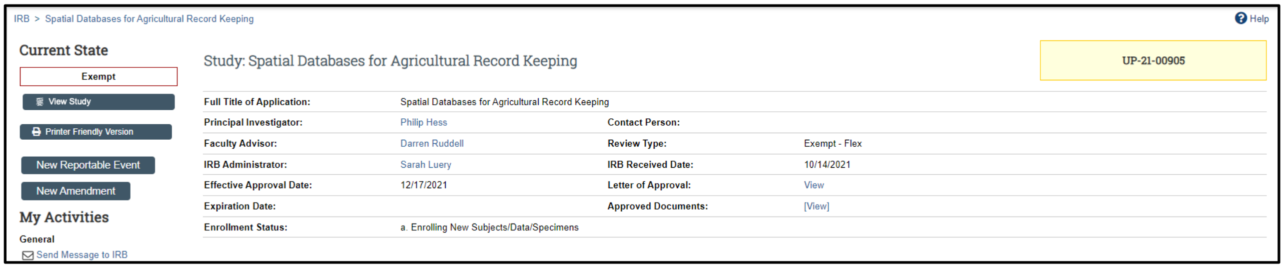
c. Data Analysis

i. The survey results will be compared with the authors research as well as their experiences working in the industry to describe the need for a spatial database and to design and implement a demonstration of said database. Archival farm records will be used to populate the database and show its benefits to farm management.

ii. Primary data will be collected as notes taken during interview. Secondary data already exists as spreadsheets and word documents.

Protocol Created by Philip Hess from IRB Template.

Appendix B IRB Approved Exemption



Screenshot of approved exemption from the IRB through iStar interface.

Appendix C Interview Script

Interview Script:

Hello __ This is Philip Hess, I am a masters student in the GIST program at USC. I am doing my thesis project about regenerative agriculture, more specifically data management and record keeping for diverse farms.

Thank you for participating in this research!

There are a few main topics I would like to discuss with you: general farming practices, current data collection and storage methods, and data/analytical needs.

General farming Practices

- What size is your farm? How many employees? Full time, seasonal, or contractors?
- What do you grow? How many species? How many types of crops?
- Do you think the spatial relationship between features is important on a diverse farm?
- What are your main fertilization, pest, and disease management strategies?

Current data collection and storage methods

- What information do you need to know about each type of crop?
- Do you record this information? If so, is it on paper or electronically? If electronically, is it stored in a word processing document, spreadsheet, database, or other form? Is this how you have always stored records?
- Do you record the location of everything you grow?
- How accessible is this information to other departments or other farm workers?
- How accessible/complete is data from previous years?
- Do you have any old farm records or documents that I can review and use to populate a sample database?

Data/ analytical needs

- What is most lacking about your current record keeping system?
- Do you, or would you be willing to, pay licensing fees for a data management system?
- What kind of analysis can you do using your data (what do you use it for, what decisions does it inform)?
- Is there any type of data that you do not currently collect or record but would be useful to have? Would this help with any new analysis or insights?

Do you have any comments, questions, suggestions, or ideas that you would like to share with me about anything we have talked about?

I value your opinion as an expert and daily practitioner in the regenerative agriculture movement. I plan to use some of the information from this interview, along with other research I have done to develop and populate a spatial database to hold agricultural records for a small diverse farm. I hope this work is interesting and useful to you, and if so I can send you a copy of the thesis when it is complete.

Thank you again for your time, and feel free to contact me with any further questions.

Script created by Philip Hess.

Appendix D Database Creation Script

```
--*** FarmDB Master Script  ***--
--** DB Creation **--
CREATE DATABASE "FarmDB"
   WITH
   OWNER = postgres
   ENCODING = 'UTF8'
   LC_COLLATE = 'English_United States.1252'
   LC_CTYPE = 'English_United States.1252'
   TABLESPACE = pg_default
   CONNECTION LIMIT = -1;
COMMENT ON DATABASE "FarmDB"
   IS 'Demonstration database holding agricultural records for farm management';
--** Add Extensions **--
CREATE EXTENSION IF NOT EXISTS postgis
   SCHEMA public
   VERSION "3.1.4";
CREATE EXTENSION IF NOT EXISTS postgis_raster
   SCHEMA public
   VERSION "3.1.4";
CREATE EXTENSION IF NOT EXISTS postgis_topology
   SCHEMA topology
   VERSION "3.1.4";
--** Create tables and relationship constraints **--
--* Farm Plot and Observations*--
CREATE TABLE "FarmPlot" (
  "plotID" numeric PRIMARY KEY,
  "name" text UNIQUE,
  "type" text,
  "loc" geometry
);
CREATE TABLE "Observations" (
  "obsID" numeric PRIMARY KEY,
  "plot" text,
  "date" date,
  "notes" text,
  "loc" geometry,
   FOREIGN KEY ("plot")
     REFERENCES "FarmPlot"("name")
                    ON DELETE SET NULL
);
--** Animal Records **--
CREATE TABLE "AnimalPack" (
  "packID" numeric PRIMARY KEY,
  "name" text UNIQUE,
  "type" text
);
CREATE TABLE "PackGraze" (
  "grazeID" numeric PRIMARY KEY,
  "pack" text,
  "plot" text,
  "start" timestamp,
  "end" timestamp,
  "loc" geometry,
   FOREIGN KEY ("plot")
     REFERENCES "FarmPlot"("name")
                    ON DELETE SET NULL,
   FOREIGN KEY ("pack")
     REFERENCES "AnimalPack"("name")
                    ON DELETE SET NULL
);
CREATE TABLE "PackFeed" (
  "feedID" numeric PRIMARY KEY,
  "pack" text,
  "date" date,
  "food" text,
  "amt" numeric,
   FOREIGN KEY ("pack")
     REFERENCES "AnimalPack"("name")
                    ON DELETE SET NULL
);
CREATE TABLE "Animals" (
  "anID" numeric PRIMARY KEY,
  "type" text,
  "name" text,
  "breed" text,
  "gender" text,
  "bDay" date,
  "arrivDay" date,
  "starNumb" numeric,
  "pack" text,
  "prosDate" date,
  "prosNumb" numeric,
  "notes" text,
   FOREIGN KEY ("pack")
     REFERENCES "AnimalPack"("name")
                    ON DELETE SET NULL
);
CREATE TABLE "AnimalMedicine" (
  "treatID" numeric PRIMARY KEY,
  "anID" numeric,
  "date" date,
  "treat" text,
  "notes" text,
   FOREIGN KEY ("anID")
     REFERENCES "Animals"("anID")
                    ON DELETE SET NULL
);
CREATE TABLE "AnimalHarvest" (
  "harvID" numeric PRIMARY KEY,
  "anID" numeric,
  "date" date,
  "prod" text,
  "amt" numeric,
  "unit" text,
  "notes" text,
   FOREIGN KEY ("anID")
     REFERENCES "Animals"("anID")
                    ON DELETE SET NULL
);
--** Plant Records **--
CREATE TABLE "Species" (
  "specID" numeric PRIMARY KEY,
  "comName" text,
  "variety" text,
  "type" text,
  "bloomSzn" text,
  "notes" text
);
CREATE TABLE "SeedMix" (
  "sedMixID" numeric PRIMARY KEY,
  "notes" text
);
CREATE TABLE "SpeciesMix" (
  "speMixID" numeric PRIMARY KEY,
  "sedMix" numeric,
  "specID" numeric,
  "amt" numeric,
   FOREIGN KEY ("specID")
     REFERENCES "Species"("specID")
                    ON DELETE SET NULL,
   FOREIGN KEY ("sedMix")
```

```
    REFERENCES "SeedMix"("sedMixID")
                        ON DELETE SET NULL
);
CREATE TABLE "PlantingEvent" (
  "plantID" numeric PRIMARY KEY,
  "date" date,
  "type" text,
  "plot" text,
  "species" numeric,
  "sedMix" numeric,
  "stage" text,
  "numb" numeric,
  "unit" text,
  "endDate" date,
  "notes" text,
  "loc" geometry,
   FOREIGN KEY ("plot")
    REFERENCES "FarmPlot"("name")
                        ON DELETE SET NULL,
   FOREIGN KEY ("sedMix")
    REFERENCES "SeedMix"("sedMixID")
                        ON DELETE SET NULL,
   FOREIGN KEY ("species")
    REFERENCES "Species"("specID")
                        ON DELETE SET NULL
);
CREATE TABLE "PlantPressure" (
  "presID" numeric PRIMARY KEY,
  "plantID" numeric,
  "date" date,
  "genPres" text,
  "specPres" text,
  "damage" text,
  "notes" text,
   FOREIGN KEY ("plantID")
    REFERENCES "PlantingEvent"("plantID")
                        ON DELETE SET NULL
);
CREATE TABLE "PlantHarvest" (
  "harvID" numeric PRIMARY KEY,
  "plantID" numeric,
  "date" date,
  "units" text,
  "amt" numeric,
  "quality" text,
  "notes" text,
   FOREIGN KEY ("plantID")
    REFERENCES "PlantingEvent"("plantID")
                        ON DELETE SET NULL
);
--** Fertility Records **--
CREATE TABLE "FertilityMaterial" (
  "matID" numeric PRIMARY KEY,
  "type" text,
  "name" text,
  "startDate" date,
  "endDate" date,
  "source" text,
  "notes" text,
  "loc" geometry
);
CREATE TABLE "MaterialMix" (
  "matMixID" numeric PRIMARY KEY,
  "notes" text
);
CREATE TABLE "FertilityMix" (
  "fertMixID" numeric PRIMARY KEY,
  "matID" numeric,
  "matMix" numeric,
  "amt" numeric,
          FOREIGN KEY ("matID")
    REFERENCES "FertilityMaterial"("matID")
                        ON DELETE SET NULL,
   FOREIGN KEY ("matMix")
    REFERENCES "MaterialMix"("matMixID")
                        ON DELETE SET NULL
);
CREATE TABLE "FertilitySpread" (
  "applicID" numeric PRIMARY KEY,
  "date" date,
  "plot" text,
  "method" text,
  "material" numeric,
  "matMix" numeric,
  "unit" text,
  "amt" numeric,
  "notes" text,
  "loc" geometry,
   FOREIGN KEY ("plot")
    REFERENCES "FarmPlot"("name")
                        ON DELETE SET NULL,
   FOREIGN KEY ("material")
    REFERENCES "FertilityMaterial"("matID")
                        ON DELETE SET NULL,
   FOREIGN KEY ("matMix")
    REFERENCES "MaterialMix"("matMixID")
                        ON DELETE SET NULL
);
CREATE TABLE "CompostTurn" (
  "turnID" numeric PRIMARY KEY,
  "pileID" numeric,
  "date" date,
  "wtrAmt" text,
  "notes" text,
   FOREIGN KEY ("pileID")
    REFERENCES "FertilityMaterial"("matID")
                        ON DELETE SET NULL
);
CREATE TABLE "CompostTemps" (
  "tempID" numeric PRIMARY KEY,
  "pileID" numeric,
  "date" date,
  "high" numeric,
  "low" numeric,
  "avg" numeric,
  "moisture" text,
  "notes" text,
   FOREIGN KEY ("pileID")
    REFERENCES "FertilityMaterial"("matID")
                        ON DELETE SET NULL
);
```

SQL code written by Philip Hess.

Appendix E Table and Attribute Descriptions

TableName	AttributeName	DataType	Description	Notes
FarmPlot			*Outlines areas on the farm (garden plots, pastures, orchard blocks etc.)*	
	plotID	numeric	Number assigned to each farm plot	Primary Key
	name	text	Name of farm plot	Alternate Key
	type	text	General farm area or department (garden, orchard, pasture etc.)	
	loc	geometry	Location of farm plot (polygon)	
Observations			*Records general observations and notes about the farm*	
	obsID	numeric	Number assigned to each observation	Primary Key
	plot	text	Farm plot where observation was made	Foreign Key (FarmPlot.name)
	date	date	Date of observation	
	notes	text	Description of observation	
	loc	geometry	Location of observation	
AnimalPack			*Groups animals together in a pack (cow herds, chicken coops, bee hives etc.)*	
	packID	numeric	Number assigned to each animal pack	Primary Key
	name	text	Name of animal pack	Alternate Key
	type	text	Type of animal in pack (Chickens, cows, bees etc.)	
PackGraze			*Records time and location of animal pack movements*	
	grazeID	numeric	Number assigned to each pack grazing event	Primary Key
	pack	text	Name of animal pack grazing	Foreign Key (AnimalPack.name)
	plot	text	Name of farm plot being grazed	Foreign Key (FarmPlot.name)
	start	timestamp	Date and time that grazing this location begins	
	end	timestamp	Date and time that grazing this location ends	
	loc	geometry	Location of grazing event	
PackFeed			*Records supplemental feed given to animal packs*	
	feedID	numeric	Number assigned to each pack feeding event	Primary Key

	pack	text	Name of animal pack being fed	Foreign Key (AnimalPack.name)
	date	date	Date that pack is fed	
	food	text	Type of food fed (alfalfa, corn, minerals etc.)	
	amt	numeric	Number of servings of food fed	
Animals			*Records general information about individual farm animals*	
	anID	numeric	Number assigned to each animal or group of animals	Primary Key
	type	text	General species of animal (chicken, cow, bee)	
	name	text	Name of animal	
	breed	text	Breed or species of animal	
	gender	text	Gender and fertility of animal (hen, bull, heifer etc)	
	bDay	date	Birthday of animal	
	arrivDay	date	Date animal arrived on farm	
	starNumb	numeric	Starting number of animals represented (1 cow, or 15 chickens)	
	pack	text	Name of animal pack that animal belongs to	Foreign Key (AnimalPack.name)
	prosDate	date	Date that animal is processed/ sold (last day on farm)	
	prosNumb	numeric	Number of animals processed (shows if chickens have died)	
	notes	text	Additional information about animal	
AnimalMedicine			*Records individual medical treatments given to farm animals*	
	treatID	numeric	Number assigned to each time an animal is given a medical treatment	Primary Key
	anID	numeric	Number identifying which animal is receiving treatment	Foreign Key (Animals.anID)
	date	date	Date of treatment	
	treat	text	Description of medical treatment or medicine	
	notes	text	Additional information about treatment application	
AnimalHarvest			*Records harvesting of animal products (eggs, beef, honey)*	
	harvID	numeric	Number assigned to each animal harvesting event	Primary Key
	anID	numeric	Number identifying which animal is being harvested	Foreign Key (Animals.anID)

	date	date	Date of harvesting animal products	
	prod	text	Product harvested (eggs, beef, chicken meat, honey etc.)	
	amt	numeric	Amount harvested	
	unit	text	Unit of amount harvested (dozen, lbs etc.)	
	notes	text	Additional information about animal harvesting event	
Species			*Records general information of plant species on farm*	
	specID	numeric	Number assigned to each plant species	Primary Key
	comName	text	Common or general name of plant species	
	variety	text	General plant family or plant variety name	
	type	text	General area or department using species (garden, habitat, orchard etc.)	
	bloomSzn	text	General bloom season (early summer, mid spring, late fall etc.)	
	notes	text	Additional information about plant species	
SeedMix			*Database table to access a mixture of species*	
	sedMixID	numeric	Number assigned to each seed mixture	Primary Key
	notes	text	Information about seed mix (nitrogen cover crop, pollinator row mix etc.)	
SpeciesMix			*Database table to define a mixture of species*	
	speMixID	numeric	Number assigned to each species mix	Primary Key
	sedMix	numeric	Number identifying which seed mix this belongs to	Foreign Key (SeedMix.sedMixID)
	specID	numeric	Number identifying which species used in this seed mix	Foreign Key (Species.specID)
	amt	numeric	Number of seeds of this species used in mixture	
PlantingEvent			*Documents when, where, and what species are planted*	
	plantID	numeric	Number assigned to each planting event	Primary Key
	date	date	Date of planting	
	type	text	General purpose of planting (cover crop, habitat, garden, orchard etc.)	
	plot	text	Name identifying plot being planted on	Foreign Key (FarmPlot.name)
	species	numeric	Number identifying which species is being planted (instead of seed mix)	Foreign Key (Species.specID)

	sedMix	numeric	Number identifying which seed mixture is being planted	Foreign Key (SeedMix.sedMixID)
	stage	text	Stage of plants being planted (seeds, 4in pot, 1 gal pot)	
	numb	numeric	Number of plants planted	
	unit	text	unit of number planted (lbs, seeds, trees etc.)	
	endDate	date	Date of removal or plant death	
	notes	text	Additional information about planting event	
	loc	geometry	Location of planting event	
PlantPressure			*Records pest and disease damage for planting events*	
	presID	numeric	Number assigned to each record of plant damage	Primary Key
	plantID	numeric	Number identifying which plants are experiencing pressure	Foreign Key (PlantingEvent.plantID)
	date	date	Date of pest or disease observation	
	genPres	text	General pressure (pest, disease, weather etc.)	
	specPres	text	Specific pressure (aphids, root rot, sunburn etc.)	
	damage	text	Level of damage caused so far (low, medium, high etc.)	
	notes	text	Additional information about plant damage	
PlantHarvest			*Records harvesting of plant products (orchard fruits, garden crops etc.)*	
	harvID	numeric	Number assigned to each time plants are harvested	Primary Key
	plantID	numeric	Number identifying which plant is being harvested	Foreign Key (PlantingEvent.plantID)
	date	date	Date that plant is harvested	
	units	text	Unit of harvest (lbs, crates etc.)	
	amt	numeric	Amount harvested	
	quality	text	Quality of produce harvested	
	notes	text	Additional information about plant harvest event	
FertilityMaterial			*Records general information of fertility material used on farm (compost, minerals etc.)*	
	matID	numeric	Number assigned to each fertility material	Primary Key
	type	text	Type of fertility material (pesticide, fertilizer, compost pile, compost tea etc.)	

	name	text	Name of fertility material (seaweed, zinc, pile name etc.)	
	startDate	date	Start date of material on farm	
	endDate	date	Final date of use on farm	
	source	text	Source of fertility material (on farm, from online, from neighbor etc.)	
	notes	text	Additional Information about fertility material	
	loc	geometry	point, line, or polygon location where material is stored	
MaterialMix			*Database table to access a mixture of fertility materials*	
	matMixID	numeric	Number assigned to each material mixture	Primary Key
	notes	text	Information about material mix (Tea with prep, etc)	
FertilityMix			*Database table to define a mixture of fertility materials*	
	fertMixID	numeric	Number assigned to each fertility mixture	Primary Key
	matID	numeric	Number identifying which materials used in this fertility mix	Foreign Key (FertilityMaterial .matID)
	matMix	numeric	Number identifying which material mix this belongs to	Foreign Key (MaterialMix.mat MixID)
	amt	numeric	Number of seeds of this species used in mixture	
FertilitySpread			*Documents when, where, and what fertility materials are applied on the farm*	
	applicID	numeric	Number assigned to each application of fertility materials	Primary Key
	date	date	Date of fertility application	
	plot	text	Name of plot being spread on	Foreign Key (FarmPlot.name)
	method	text	Method of application (foliar spray, fertigation, spread, root soak etc.)	
	material	numeric	Number identifying material applied (Instead of material mixture)	Foreign Key (FertilityMaterial .matID)
	matMix	numeric	Number identifying material mixture applied	Foreign Key (MaterialMix.mat MixID)
	unit	text	Unit of material applied	
	amt	numeric	Amount of material applied	
	notes	text	Additional information about fertility application event	

	loc	geometry	Location that fertility was applied	
CompostTurn			*Records information about turning of compost piles*	
	turnID	numeric	Number assigned to each compost turn	Primary Key
	pileID	numeric	Number identifying which compost pile is being turned	Foreign Key (FertilityMaterial .matID)
	date	date	Date of compost turn	
	wtrAmt	text	Amount of water used in turn (low, medium, high etc.)	
	notes	text	Additional information about the compost turn or pile	
CompostTemps			*Records information on temperature of compost piles*	
	tempID	numeric	Number assigned to each time compost temperatures are measured	Primary Key
	pileID	numeric	Number identifying which compost pile is being measured	Foreign Key (FertilityMaterial .matID)
	date	date	Date that temperature measured	
	high	numeric	High temperature of pile	
	low	numeric	Low temperature of pile	
	avg	numeric	Average temperature of pile	
	moisture	text	Moisture of pile	
	notes	text	Additional information about compost temps or pile	

Created by Philip Hess.

Appendix F Database Queries Script

```
--*** Queries In Thesis ***--

--Database Queries –

/* Query 1: Shows all records from Animals table.
SELECT * FROM "Animals" ;
*/

/* Query 2: Shows certain columns from Animals table.
SELECT an."type", an."name", an."breed"
FROM "Animals" an ;
*/

/* Query 3: Shows specific columns from Animals table that represent cows.
--SELECT an."type", an."name", an."breed" FROM "Animals" an WHERE an.type = 'cow' ORDER BY
an."arrivDay" ASC ;
SELECT an."type", an."name", an."breed"
FROM "Animals" an
WHERE an.type = 'cow';
*/

-- Relational Queries --

/* Query 4: Shows name, breed, and medical treatments of all cows.
SELECT an.name, an.breed, am.treat
FROM "Animals" an JOIN "AnimalMedicine" am
	ON an."anID" = am."anID"
WHERE an."type" = 'cow';
*/

-- Temporal Queries --

/* Query 5: Shows variety, common name, and plant date of garden crops planted in first 2 months of 2018.
SELECT sp."variety", sp."comName", pe."date" as planted
FROM "Species" sp JOIN "PlantingEvent" pe
	ON pe."species" = sp."specID"
WHERE pe."date" BETWEEN '2018-01-01' AND '2018-03-01'
	AND sp."type" = 'garden';
*/

/* Query 6: Finds age of all cows currently on farm (Nov. 15 2019) in weeks.
SELECT an."name",
	('2019-11-15'- an."bDay")/7 as weeksOld
FROM "Animals" an
WHERE an."type" = 'cow'
	AND an."prosDate" IS NULL
	AND ('2019-11-15'- an."arrivDay")>= 0;
*/

-- Spatial Queries --

/* Query 7: Shows name, type and location of all farm plots.
```

```
SELECT fp."name", fp."type", fp."loc"
FROM "FarmPlot" fp;
*/

/* Query 8: Finds area (acres) and perimeter (meters) of each farm plot.
SELECT n."name",
        ST_AREA(n.loc::geography)*0.00024710538 as acres,
        ST_Perimeter(n."loc"::geography)as meters,
        n."loc"
FROM "FarmPlot" n;
*/

/* Query 9: Finds current location of animal packs (April 16, 2019).
SELECT  ap."name" pack, fp."name" location, fp."loc"
FROM "AnimalPack" ap JOIN "PackGraze" pg ON ap."name" = pg."pack"
        JOIN "FarmPlot" fp ON pg."plot" = fp."name"
WHERE ('2019-04-16' BETWEEN pg."start" AND pg."end")
        OR ('2019-04-16' <= pg."start" AND pg."end" IS NULL);
*/

/* Query 10: Query 10: Displays a summary of each farm plot in 2018 including the name of the plot, the total
                number of days it has been grazed by cows and by chickens, the amount of compost
                spread per acre, and the number of times planted that year.
WITH gz as ( SELECT pg."plot",
                justify_hours (SUM( CASE WHEN ap."type" LIKE '%chickens' THEN (pg."end" -
pg."start") ELSE '0h' END)) AS "Chicken Graze",
                justify_hours(SUM( CASE WHEN ap."type" = 'cows' THEN (pg."end" - pg."start")
ELSE '0h' END)) AS "Cow Graze"
            FROM "PackGraze" pg JOIN "AnimalPack" ap on pg."pack" = ap."name"
            WHERE pg."start" BETWEEN '2018-01-01' AND '2018-12-31'
            GROUP BY pg."plot"),
        cmt as ( SELECT  frs."plot",
                        SUM ( frs."amt" * CASE frs."unit" WHEN 'tons' THEN 2000 WHEN
'wheelbarrows' THEN 175 WHEN 'buckets' THEN 25 ELSE 0 END
                            / (ST_AREA(fp."loc"::geography)*0.00024710538 )) AS "Compost
lbs/acre"
                FROM "FertilitySpread" frs JOIN "FarmPlot" fp ON frs."plot" = fp."name"
                WHERE frs."date" BETWEEN '2018-01-01' AND '2018-12-31'
                GROUP BY frs."plot"),
        ar as (SELECT * FROM "FarmPlot" fp),
        ptd as (SELECT pe."plot", COUNT( pe."plantID") AS "Times Planted"
                FROM "PlantingEvent" pe
                WHERE pe."date" BETWEEN '2018-01-01' AND '2018-12-31'
                GROUP BY pe."plot")
SELECT ar."name", gz."Cow Graze", gz."Chicken Graze", cmt."Compost lbs/acre", ptd."Times Planted", ar."loc"
FROM ar FULL JOIN gz on ar."name" = gz."plot" FULL JOIN cmt ON ar."name" = cmt."plot" FULL JOIN ptd
ON ar."name" = ptd."plot";
*/
```

Code written by Philip Hess.