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Extracting Weather Information from a Plantation Document

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Abstract. The authors introduce a method for extracting weather and climate data from a historical plantation document. They demonstrate the method on a document from Shirley Plantation in Virginia (USA) covering the period 1816–1842. They show how the resulting data are organized into a spreadsheet that includes direct weather observations and information on various cultivars. They then give two examples showing how the data can be used for climate studies. The first example is a comparison of spring onset between the plantation era and the modern era. Modern median final spring freeze event (for the years 1943–2017) is occurring a week earlier than the historical median (for the years 1822–1839). The second analysis involves developing an index for mid-summer temperatures from the timing of first malaria-like symptoms in the plantation population each year. The median day when these symptoms would begin occurring in the modern period is a month and a half earlier than the median day they occurred in the historical period. The authors suggest that this type of local weather information from historical archives, either direct from observations or indirect from phenophase timing, can be useful toward a more complete understanding of climates of the past.

1 Introduction

Weather data from historical periods is important for understanding climates of the past. Instrumental weather data go back only a few centuries but historical document contain observations about the environment that, as a collection, can be used to understand the climate in previous centuries. In particular, plantation document are an excellent source of useful observations about the local environment. These observations when organized and collated can enrich and extend our understanding of local climates back into the early nineteenth century providing a broader context in which to understand climate variability and climate change.

Plantation documents, a source for considerable historical research, are overlooked as a source for environmental research data, with a few notable exceptions (Burris et al., 2018; Mock, 2013; Dupigny-Giroux and Mock, 2009). Plantation document often contain regular observations about the weather (Baptist, 2014; Mock et al., 2007; Phillips, 1918; Stampp, 1956). Where they have, typically only a few ordinal data points are used in support of historical instrumental data (Dupigny-Giroux and Mock, 2009; Mock et al., 2007). Instrumental records are indeed available at certain times and places. For instance, Thomas Jefferson kept thermometer and barometer readings for his Monticello Plantation for many years (Jefferson, 1776). But more typically, weather observations come in the form of ordinal observations. For instance, temperature might be described as "hot,"

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"freezing," or "mild," to name a few. Similar observations were made about wind conditions, cloud conditions, precipitation, and hydrology.

Plantation document contain regular observations about crops, which can provide a proxy for the weather conditions under which they grow. For example, studies have used records of phenophases – stages in the life cycle – to study spring advancement or to reconstruct temperatures over past centuries (Aono and Kazui, 2008; Chuine et al., 2004; Primack and Miller-Rushing, 2012; Holopainen et al., 2013). These studies typically use one phenophase description from a single species. As a result, they are restricted to one data point per year. For instance, this might produce the number of days spring has advanced in a location over time, spring mean temperatures, or summer mean temperatures. In contrast, plantation document typically contain multiple phenophase observations for several crops each year, making them a particularly valuable resource for proxy weather conditions.

The goal of this paper is to make plantation documents approachable to researchers interested in local weather conditions of the past. The objective is to describe the process of turning historical document into accessible scientific data. Here we use a document with daily entries from Shirley Plantation located in Charles City County, Virginia, USA covering the period of 1820–1842. The resulting database is then analyzed in two separate case studies. Replication of our method for analyzing documents available from other plantations likely will need some adjustments but much of the organization structure should translate. Importantly, data of this kind covering a wider range of dates and other locations can be valuable for understanding our past climate.

This paper expands on earlier efforts to use a plantation document as a source for historical weather data and offers a structured method for turning a plantation document into usable data for climate research. Section 2 provides a brief history of extracting weather data from historical document. Section 3 describes how information from a historical document of Shirley Plantation is organized as a database. Section 4 discusses the agricultural variables that are included in the database. Section 5 describes the resulting database and illustrates how these data can be used for addressing scientific questions. Finally, section 6 provides a summary and some caveats and considerations for future studies.

2 Weather Data From the Historical Document

The use of written historical documents as a source of weather data is not new. For example, Henry David Thoreau's documents have been used to study spring advancement around Walden Pond in Massachusetts (Primack and Miller-Rushing, 2012). Ship logs have been used to study climate conditions at sea for periods before remote sensing (Allan et al., 2016) as well as historical shifts in geomagnetism and other applications (Jonkers, 2003; Wilkinson, 2005). More recently, municipal documents from southeastern China have been used to reconstruct typhoons covering the past thousand years (Chen et al., 2018). Climatologists have reconstructed several types of data from historical documents. These include recovering instrumental records, but also utilizing diaries, newspapers, and other personal document to reconstruct hurricanes, typhoons, and other severe weather events (Allan et al., 2016; Daly et al., 2007; Chen et al., 2018; Mock et al., 2007; Camuffo and Jones, 2014).

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Historical documents have also yielded several databases on phenological responses to climate change. These came out of the 19th century naturalist movement. In-depth observational document exist for many sites, but are often stored with the document pertaining to the authors' literary works. Historians and scientists are only beginning to tap the biological and ecological data produced in that century, while other sources and earlier documents remain largely unused. An example are the Marsham family papers, which contain a set of observations collected by several members of the family over the course of three generations. They were interested in the life cycles of plants and animals on their land and they recorded plant stages like leafing, flowering, and fruiting. These observations have seen some use over the years in ecological studies (Margary, 1926; Roberts et al., 2015; Sparks and Carey, 1995). Another example are a set of phenological observations from Estonia that have been found for a similar period. These have been used to explore how changes in climate have altered the life cycles since industrialization began (Ahas, 1999; Margary, 1926; Primack and Miller-Rushing, 2012; Roberts et al., 2015; Sparks and Carey, 1995). There have also been applications of historical observations of phenology to reconstruct past climate conditions where instrumental data are not available or have not been found. This research has been used to show increasing temperatures in recent decades when compared to earlier centuries (Aono, 2015; Aono and Kazui, 2008; Chuine et al., 2004; Holopainen et al., 2013). Plantation document offer another source of data covering earlier periods.

3 The Shirley Plantation Document

This section describes how information from a particularly rich Shirley Plantation document was organized into a database. Shirley Plantation is one of the oldest and largest plantations in the United States. It is located in Charles City County, Virginia, USA (Figure 1). Hill Carter inherited it in 1806 and started documenting events occasionally in a log book starting in 1816. He began keeping daily entries in 1820 that continued until his death in 1875. Hill Carter's son, Robert Randolph Carter (1825–1888), took over management of the plantation and continued documenting events until his death. The Shirley Plantation document refers to this single yet extensive log book.

The primary crops grown on the Shirley Plantation during this time as noted in the log book included wheat, corn, and clover. Several other species were grown intermittently (see Figure 2 for a full list of crops and the years they were mentioned in the document). When and how often crops showed up in the document varied. Staple crops like wheat and corn appeared every year, while other species like beans were rarely mentioned. The set of crops remained consistent over the period but it took a few years for Hill Carter to begin regular entries concerning them, resulting in the years 1816–1819 having very few entries. The first two years of consistent entries (1820–1821) were defined by infrequent observations. For instance, missing are entries of when the first and last freezes occurred. Beginning in 1822, Carter kept more consistent documentation. Entries became more common until they were on a regular daily basis. The level of detail in the individual entries increased over this period (Figure 3).

Each year the number of observations increased throughout the growing season, culminating in the harvest of corn in the fall. This general cycle was disrupted by business trips to New York by Hill Carter. These trips were usually taken in October of each year, resulting in minimal entries for these periods. This can be seen in Figure 4, where the number of entries usually dipped in October. Hill Carter had the overseer make entries in his absence, with mixed results. Upon Hill Carter's return from these trips, he often expressed dissatisfaction about the how things were managed and documented by the overseer. After firing the overseer for this mismanagement in 1824, and then taking them back on, more consistent entries were kept during these trips, but these were still not up to the same standards. He did not make the journey in 1825, leaving that year's entries unbroken. After 1825, the trips resumed and the entries remained consistent for the rest of the years.

3.1 Observation Type

There is a range of observations within the document (Table 1). We group them into seven broad types. Weather observations have the most entries followed by labor and agriculture (Figure 5). Other categories include operations, human, livestock, and accounting. Typically, multiple observations are made in a single day's log entry. For this reason, there are multiple entries for a single day. A "type of observation" variable allowed for filtering the data based on activity (Figure 5).

3.1.1 Weather observations

The bulk of observations (13,461) made at Shirley Plantation were about the weather. Most days had at least one weather observation, even on Sundays, when there typically was no agricultural work done on the plantation. There were often two weather observations per day. One observation would involve temperature. The other would involve cloud conditions and precipitation. Most temperature and precipitation observations were ordinal and subject to the observer's definitions. One person's rain shower is another's sprinkle, and how they define these can change, both over a lifetime and from season to season. A pleasant day by summer standards may be warm by winter standards. A decade of unusually warm temperatures might lead an observer to start defining above normal temperatures as normal, and think of the return to the standard conditions as unseasonably cool. Changes to the baseline perception of what is normal complicates interpretation. Despite the ordinal nature of these data, we argue that researchers can glean information from such a long-term document.

3.1.2 Agriculture observations

About one third of observations were considered agricultural. Most of the agricultural observations had to do with the work being done on the crops. This included activities like sowing, weeding, and harvesting. There were also discussions of problems encountered: for instance, weather–related problems like blow–overs and water damage from rain. There were also observations about pests including wheat rust, chinch bugs, and cockle (See Table 2 for definitions, and Table 3 for alternative terms and archaic spellings used in the document).

Direct observation of phenophases are rare. There are a few mentions of phases such as the day that a crop emerged, or when a field of grain started heading. Other phenophases can be deduced from agricultural activity. For instance, most entries do not explicitly say that the cotton crop had leafed. However, cotton crops would be weeded regularly in their early stages. This would continue until they leafed. At this point the leaves would shade out the weeds. Laborers, both free and enslaved, would be redirected, often to weeding corn. There are other ways to determine that the cotton had achieved the leafing stage.

Mentions of weeding the cotton crop might end, or the entry may say that the laborers were now weeding the corn (Toman, 2002).

3.1.3 Labor and Operation Observations

While many entries are about weather and crops, there is also information on operations and labor conducted on the plantation. Such activities were performed before planting and after harvesting. These ranged from field preparation like plowing, to thrashing out and delivering grain. While this may seem like a straightforward part of plantation life, plantations were a confluence of multiple agricultural traditions, coming from many regions and linguistic origins. The result is a patchwork of synonyms, meanings, and spellings, and terms came in archaic and modern forms.

Multiple terms are used to describe similar preparation activities. Each is typically associated with a particular crop. For instance, cutting, onioning, and picking out were terms for harvesting associated with grains, onions, and cotton, respectively. But picking out could also refer to things grown in patches like peas and pumpkins (spelt in the archaic form "pumpions" in the document). All of them refer to harvesting those crops. There were multiple spellings for some words as well. For Instance, “bauks,” strips of land where corn was planted (Table 2), was alternatively spelled as “balks” and “baulks.” Plaster was sometimes spelled as “plaister.” Table 3 lists some of the more common terms with alternative synonyms or spellings. Table 2 contains definitions for some of these less common and archaic terms.

During this period, plantation owners experimented with various soil treatments. For instance, the enslaved laborers occasionally limed a field. This practice of applying crushed limestone before planting would make the soil less acidic. This could help plants grow more readily and combated soil degradation. Marl was produced by altering the chemical structure of lime by baking it. This made it more effective than lime, but fulfilled the same function. Other treatments were intended to improve the nutrients of the soil. Plastering is a similar activity to liming, in which gypsum or some other plaster is spread on the field to replace depleted nutrients. Manuring was another common preparatory activity. this referred to spreading manure on a field as a fertilizer. It was usually done just prior to sowing activities. Green manures and cover crops were also common. Peas and beans were often plowed under instead of being harvested in an effort to improve deteriorated fields. These preparatory activities are not directly related to phenology but they can provide useful information. For example, in the absence of detailed documentation, these preparatory activities can inform the researcher that seeds have not been planted for that crop yet.

3.1.4 Additional Entries

Entries throughout rest of the document fall into the less common categories. These minor categories were grouped into Accounting, Human, and Livestock (Table 1). For example, accounts of how much grain was produced and sold can indicate how heavily impacted harvests were by weather conditions. Human health and activities were often directly impacted by the weather. Observations of when people were sick were made regularly. This typically included how many people were sick and and what they were believed to be sick with. Illnesses, deaths, and other observations about the human population can be useful for showing how often conditions for endemic diseases like influenza and malaria occurred at the plantation. Non-agricultural labor activities can inform the entries about prevailing conditions, such as repairing flood and hurricane damage. While large animal phenology tends not to be effected by spring advancement or other aspects of climate change, secondary and tertiary impacts like trophic mismatches can impact livestock and their phenophases (Post and Forchhammer, 2008). Health problems and deaths among the livestock from extreme heat also gives insight into weather conditions.

4 Agricultural Variables

This section discusses the agricultural variables that were put in the database. We cover the specific information contained in each entry. The species and cultivar variables provide information on the plant or animal being observed. Description provides the account given in the plantation document. The categorical and numerical variables contain the specific information that can easily be used in quantitative analysis, such as how many bushels were harvested, or that the plantation was experiencing drought conditions.

4.1 Species

Where the species was specified, the information was included. For nonagricultural activity types, or when the species was not specified, a "Not Available" (NA) value was entered. For instance, if the entry states that corn is being resown, then the species value would be “corn.” Sometimes more than one species would be involved. The most common case of this was when a pest was effecting one of the crops.In these cases, the crop being grown would be put in the species variable. The pest species would be placed in the categorical variable. Figure 2 lists all species encountered in the Shirley Plantation document and the years that species was mentioned.

4.2 Cultivar

Specific cultivars of species were occasionally mentioned. Table 4 lists the cultivars mentioned within the document for the years 1816–842. Cultivar is part of the taxonomic nomenclature applied to plant species that have been artificially selected. The nomenclature goes from the more general to the specific, and is genus, species, subspecies, cultivar. tracking the cultivar is especially useful for the nineteenth century. New cultivars were developed, experimented on, and further selected for specific traits. These efforts resulted in significant modification of the phenological and morphological traits in the crops. These modifications probably resulted in many of the crop yield gains seen in the antebellum period, as well as the expansion of the ranges of many crop species (Olmstead and Rhode, 2008a, b, 2018).

4.3 Description

The specific observation or description was entered in this variable. For instance, the specific phenophase being observed would go here. So if corn was observed to be tasseling on a certain day, the entry would read tasseling. If the document noted that the cotton was weeded for the last time and work began on weeding the corn, there would be two separate entries. There would be one entry for the end of the cotton weeding, and a separate entry for the beginning of the corn being weeded.

Types of activity for non-agricultural observations are part of this variable as well. Entries for agricultural operations were given more specificity. If some sort of soil treatment was being applied to a field, the type (such as marl, plaster, manure, etc.) would be entered here. This was also where the different type of weather observations were denoted. For instance, this variable would specify if the weather observation was about temperature, precipitation, or cloud cover. For health observations, the disease or cause of death was placed here.

The variables "Observation" and more general "Type of observation" make it easy to subset the descriptions. It is easy to just look at descriptions of agriculture activity, or to just look at when the human population was sick. The structure of the data makes it easy to input all the observations into a single database as the entries are processed. This makes the data entry more efficient while still being comprehensive, but easily reducible to a subset needed to study a particular phenomena.

This is an improvement on previous methodologies that have been more ad hoc. Instead of scouring the document for just the last spring freeze event or the flowering of a particular species, this method retains the robustness of the original document. This increases the usability of the data. Within one file, there is information on extreme weather events, phenology, public health, bioclimatology, and agronomy. Beyond the immediate concern of studying the past climate, the data has great interdisciplinary utility. It can be used for environmental and social history, economic research, epidemiology, and others. The initial investment of time is substantial, but the returns are worth it.

4.4 Categorical

The categorical or ordinal value of observations were placed here. This was most important for weather. There was usually some sort of descriptor accompanying the weather observation. For instance, if the document said that there was mist on a certain day, the categorical value would be "mist." If an observation noted that it was "cold" on a certain day, it would be entered as "cold." This is also where freezes and frosts were entered.

This applied mainly to non-agricultural activity entries, but there were a few exceptions. When a crop was damaged or destroyed by pests, the nuisance species would be entered here. For instance, when a wheat crop was destroyed by rust, the "Observation" value would be pest, and the categorical value would be the type of pest, in this case rust. When an agricultural activity, such as sowing or weeding, would begin or end, that would be entered here as well. Units for numerical values were made available here.

4.5 Numerical Entries

Numerical values were occasionally available in the document. These values are entered in the database. If 200 bushels of wheat were sold after harvesting, "bushels" would be entered in the categorical variable, and "200" would go in the numerical variable. This was used to enter a variety of observations, including the number of people sick on a given day, thermometer readings, accounting values, etc.

There were intermittent instrumental readings from a thermometer starting in 1822. Temperatures were entered on an irregular basis until the instrument fell and shattered on February 23, 1824. It was not replaced for several years. Thermometer readings did not start up again until February 4, 1835. The document did not discuss the model of thermometer or where it was

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kept. While the units were not explicitly stated, summer temperatures were entered in the nineties, making it most likely that measurements were in degrees Fahrenheit rather than degrees Celcius.

These thermometer readings were entered in short spurts at different times of the year. When present, they were typically the first thing in that day's entry. The entries' consistent location in the daily log suggests that the instrumental reading was made first thing in the morning, when the daily temperature is usually at its lowest. The end result is a fairly homogeneous document of daily minimum temperatures during a few periods. The presence of the thermometer at Shirley Plantation, as opposed to being read about in an almanac or newspaper, was confirmed when it was noted that it fell to the ground and shattered.

There were limits to the precision of the instrument itself. Without knowing the details of its manufacture, it is not possible to tell how big of a measurement error there may or may not have been. The placement of the instrument, such as in the shade or direct sunlight, could also affect readings. There could be a systematic bias in how the observer was reading the instrument, such as if the mercury or alcohol in the instrument was between two ticks, the observer might always round it up or down. It is also possible for the observer to read the instrument differently from day to day, or for their method to change over time. The documenting of observations throughout the year was also inconsistent. The observer might only remember to document the temperature when it is especially cold or hot. They might also forget to make the entry if they are especially busy. This can be random, or systematic. During the calving season each year, when the observer is working long and irregular hours, they might forget to enter the temperature. They might also think to make an entry in response to extreme weather events when they would not have usually remembered to. There can also be more traditional inhomogeneities in the entries. If the instrument is moved to a different location or height, a systematic bias can be introduced from suddenly being in direct sunlight or being closer to the ground.

4.6 Metadata

The database includes information on the time and place for each observation. This comprised information like the location of the plantation, date of observation, citation information and the name of the location. While most of these will not be directly used in the data analysis, they provide other functions. The location data can be used to geo-reference the database. Common names are useful for connecting the observations with mentions of the location in other document such as correspondences. Citation information allows for reproduction, confirmations of accuracy, and other forms of peer review. Location information will later enable areal interpolation of the data as the document from additional locations are added to the database.

5 The Database

In this section we describe the resulting database and give two examples of the types of analyses that can be done with it. The first compares final spring freezes from the historical period to modern conditions tot est for spring advancement. The second analysis looks at historical accounts of annual disease outbreaks of what is now thought to have been malaria. We use modern data to reconstruct when these outbreaks would occur, and compare the two sets of dates.

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5.1 Description

Here we provide some details about the database and then illustrate how it can be used. The Shirley Plantation document were scoured for weather and agricultural information along the lines described in the previous section and arranged into a database. The result is 22,019 observations in the database. Table 5 shows a small portion of the database covering observations during the first week of July in 1838. Reading from left to right, each successive variable becomes more specific. After the date, the most general variable, observation type is given, followed the more specific category. For instance, "agriculture" is one of the observation types. The agricultural observations for this week included "shelling", "harvesting", "problem", and "phenology". Wheat is the only species being worked on, and on four of the occasions it was specified that the cultivar of wheat being worked on was "purple straw".

We can see that on the first two days of the week, the wheat is harvested and shelled, often referred to as thrashing (See Table 3 for a variety of terms that referred to similar activity). Two problems with the crop were noted: that it was too ripe, and that part of the wheat had become tangled, making it more difficult to harvest. On the third day, there were more problems reported. A hurricane had gone through the area, causing the loss of some of the wheat crop. Additionally, some of the wheat that had been cut and left in rows (called windrows) had begun to open up and sprout. This was a result of the crop being over ripe and getting wet. For the rest of the week, the observations focus on harvesting the wheat crop, while continuing to note that it was too ripe.

There are also observations with the Observation type "Weather". Under this variable, ten of these were about temperature, with three of these also giving a thermometer reading. The other seven were ordinal observations, describing five of the days as "hot", two of the days as "cool", and one day as "warm". There were observations about cloud cover and precipitation as well. There were five "clear" days and two days with clouds and thunder storms. The 6th of July was described as windy. Rain was observed on the 1st and 2nd of July.

The database can be examined from various perspectives. For instance, the heat map in Figure 2 was constructed by using only database entries with the observation type "agriculture." The database closely reflects what was written in the historical document. For instance, if the document said that it rained and thundered, then two separate database entries would be entered. One for the rain, and one for the thunder, as is the case on July 1st, 1838 (Table 5). If something specific is required, such as days with cloud cover, the database can be subset to include only entries of "cloudy" and days with "precipitation."

5.2 Earlier spring onset

Here we illustrate how the database can be used for scientific studies. We start with investigating spring onset. Is the onset of spring occurring earlier now than it did at the time covered by the document at Shirley Plantation? Specifically, given the warming climate due to greenhouse gases from industrialization we expect that the annual dates of the last spring freeze over the period 1822–1839 (before modern industrialization) will occur later, on average, than the annual dates of the last spring freeze over the later period 1943–2017.

To examine this hypothesis we use the last date on which there was a mention of frost, freeze, or snow (after the winter) from the plantation document for each year. The start year of 1822 is the first year that mentioned freezes. We compare these dates with minimum temperature data from the nearest weather station. The weather data was retrieved from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information's (NCEI) online repository. Daily Minimum temperatures from the Richmond International Airport weather station (GHCND:USW00013740) over period January 1943 to July 2017. The station is located 20 kilometers to the Northwest of Shirley Plantation (See Figure 1 for a map of the area).

Dates are expressed as number of days into the year (day of year), with the first of January equaling one. It is possible that temperatures for the historical decade dropped below zero degrees Celsius without frost or snow being observed, so the given historical values are a more conservative measurement of the last freeze (could have been later) relative to the hypothesis. Figure 6 is a histogram of last spring freeze events in the instrumental period. The vertical black line represents the median value for the historical period. The historical database had a median end-of-freeze date of 107.5 (April 17 or 18). The modern median final spring freeze event date was 100 (April 10 or 11), or a difference of 7.5 days.

Because the historical last spring freeze data constituted a small sample size, a nonparametric one sided Wilcoxon (Mann-Whitney) signed-rank test was used to test the statistical significance of historical final spring freezes coming later in the year than in the modern instrumental period (Wilcoxon, 1945). The W value for the test was 797, with a p-value of 0.015. This indicates that the two groups' distributions differed in a marginally significant way, with modern final spring freezes occurring earlier than they did in the past. This indicates that spring onset is occurring earlier than in the historical period. The example shows how the data might be useful for comparing the past with the present. It can be used to study how differing climate conditions have impacted crop survivability, yields, and how agricultural practices have changed in response to climate variation.

5.3 "Ague and Bilious Fever" first new infection date as indicator of mid summer temperature

Before germ theory and microscopes, malaria was often diagnosed as "ague and bilious fever" (See Tables 3 and 2 for related terms and their definitions). Figure 7 shows the period each year when "ague and bilious fever" symptoms were reported on Shirley Plantation. This covers the years 1823–1842, with 1839–1841 missing data. The earliest reports of symptoms occur in mid to late July, indicating especially warm years. Most years saw outbreaks begin in September. A few years only saw mentions of ague and fever in the first few days of October. These are often reports that there were very few or no cases that year. The season typically ends before Hill Carter left on his annual trips, resulting in complete documentation for most years. The beginning of the *Plasmodium* season, the end of the *Plasmodium* season, and the length of the season between those two dates also offer important information about weather conditions. However, the end date of the season is a more complex processes.

An index of mid summer weather conditions can be constructed using historical public health data. The phenology of insects, and the parasites they carry, are sensitive to temperature (Guerra et al., 2008). Plant phenophases like flowering and harvest dates have been used to study changes in climate conditions (Aono and Kazui, 2008; Chuine et al., 2004; Primack and Miller-

Rushing, 2012). These types of indices, models, and reconstructions can be applied to other temperature dependent phenologies (Guerra et al., 2008).

Plasmodium parasite development response to temperature can be modeled similarly to how crop phenology is, by using degree days (Guerra et al., 2008), using the following formula.

$$DS = \frac{DD}{\bar{T} - 18} \tag{1}$$

Where DS is the number of days it will take for the parasite to mature (Duration of Sporogony), DD is the number of degree days required for parasite to mature, $\bar{T}$ is the daily mean temperature, and 18 is the minimal temperature threshold for degree days to accumulate for the species (Guerra et al., 2008). The sporogony of *Plasmodium*, the type of malaria parasite common in the Tidewater region of Virginia during the nineteenth century, requires 105 degree days to accumulate (Gething et al., 2011). Both the *Anopheles* mosquito and *Plasmodium* parasite respond to temperature in their development (Guerra et al., 2008). *Plasmodium vivax* is one of the mosquito borne pathogens that cause malaria. *Plasmodium falciparum* is another, more deadly, malaria causing parasite. *Plasmodium malariae* is a third, though less common *Plasmodium* pathogen (Guerra et al., 2008).

It is not necessary to diagnose specific cases of *Plasmodium* infection from the historical document. We know that it was endemic to the area. We know that the population was affected nearly every year. We know that the phenological constraints resulted in the infection season occurring in the same time period each year, just like wheat harvests or cherry blossoming (Rutman and Rutman, 1976; Merrens and Terry, 1984; Centers for Disease Control and Prevention, 2018; Guerra et al., 2008). This produces the parameter for the new index: first new cases reported. This can be represented as the day of year. There are a series of events that must occur before the first symptoms are detected. The female *Anopheles* mosquito must become infected while taking a blood meal from a human. The mean daily temperature must be warm enough for the sporogony cycle to begin. The mean temperature during sporogony must be high enough to complete the cycle within the lifespan of the mosquito host. The mosquito host must transmit it to a human. Finally, the parasite must incubate in the human host for 12–18 days (for *P. vivax* and *P. falciparum*) before symptoms appear (Guerra et al., 2008).

By the time symptoms appear, the daily mean temperature in the area has been above 18° Celsius (64.4° Fahrenheit) for two to four weeks. This can be further examined if we know what species of *Plasmodium* are endemic to a region. For instance, *P. vivax* can survive in cooler conditions better than others. Its lower temperature threshold for development allows for it to survive in regions that would be too cold for *P. falciparum*. As a result, this is the dominant species in temperate regions like south eastern England and Tidewater Virginia (US) (Guerra et al., 2008; Mann, 2015; Rutman and Rutman, 1976).

While malaria has been eradicated in Virginia, we can estimate by using temperature data when the sporological cycle (*P. vivax*) would complete. For instances, if malaria were present in Virginia today, the *Anopheles* mosquito would become infectious after a sustained warm period. Warm periods are defined using accumulated degree days. A degree day in this case is defined as the difference between the daily mean temperature and 18 when the daily mean exceeds 18° C. A sustained warm period is one in which the accumulated degree days over a 26-consecutive day period exceeds 105. Our interest is in the earliest sustained warm period date of the year where the date is the last day of the 26-day period.

Using the Richmond International Airport Weather Station temperature data, we compute the accumulated degree days above 18° C in rolling 26-day increments to determine the earliest sustained warm period each year over the period 1942–2017. We add 18 days to this date to account for incubation period (conservatively as the incubation might be faster) giving us an estimate of when we might get the first cases of malaria (onset date).

We then used the historical and expected modern onset dates as indicators of summer temperature conditions. The median first date of symptoms being documented on Shirley for the period 1822–1838 was the 230th day of the year. The median date for when symptoms would begin occurring in the modern period from 1942–2017 was the 185th day of the year (See Table 8). Median dates for malaria symptoms conditions occurred 45 days earlier in the modern period than they did in the historical period. This indicates much warmer conditions in the modern period.

Like the comparison of final spring freeze events in the first analysis, this allows a comparison to be made between ordinal data, commonly found in historical document, with numeric data from modern instruments. In this case, we compared mid summer temperature conditions across epochs. Where the first analysis allows us to compare temperatures by using observations of water undergoing a state change at 0° C, the analysis of malaria symptoms allows us to analyze summertime temperatures. The later method can be extended to any place and time where malaria was endemic and its effects documented.

6 Summary

We extracted historical environmental and weather data from a plantation document written over the period covering 1816–1842 at Shirley Plantation in Virginia, USA. We detailed the methods used to extract the data from the document and make them available as a database. The method provides a recipe for others interested in extracting data from similar historical document. The database covers 25 years of plantation entries resulting in 22,019 entries in the database. The majority of the entries are ordinal observations of weather. Currently the database contains more than 2,000 entries about agriculture that can be used for phenological based studies of climate. There are also intermittent instrumental entries. The database is available on github.

Using the database we compared historical and modern spring onset dates and showed that the median spring onset occurs a week earlier in the modern period. As the mean global temperature increases, measures of spring onset have been shown to occur earlier. These changes in temperature regimes can result in shifts in the phenology of plants and animals. Member species of an ecosystem can respond differently to these changes. Some plants will respond to spring advancement by flowering earlier in the year. Other plants are not responsive to these changes. The pollinators will have their own responses to the changing climate. The end result is disruptions to the flow of energy and resources. This has been shown to cause loss of plant populations in places like Walden pound in Massachusetts (Primack and Miller-Rushing, 2012). These trophic mismatches have also increased the infant mortality rate among caribou, which are dependent on plants being at their most nutrient rich during calving season (Post and Forchhammer, 2008). Studies like this help measure the severity of spring advancement. This can in turn be used to predict where trophic mismatches are most common and have the greatest impact. This type of information is key to planning mitigation strategies for dealing with global climate change.

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Using our database, we also showed how public health data can be used as an index for summer temperatures. Because of the temperature sensitivity of the *Plasmodium* parasite, the daily mean temperature in the area has to remain above 18° Celsius (64.4° Fahrenheit) for two to four weeks for the first new infections to begin. Thus the first appearance of new infections indicates how warm the mid summer period was each year. This in turn can be used as a proxy to study the inter-annual variability of temperature in the absence of instrumental records.

There are additional considerations to keep in mind when using the database. Although we have already put approximately 3000 work hours into the database, we are not yet half way through the Shirley Plantation document. And there is an additional 25 years of related documents maintained by Hill Carter's son. There are also other similar documents from locations throughout Virginia and the Southeastern United States. It is also important to keep in mind how these document were kept. The absence of a document does not ensure the absence of the event. Hill Carter would write down the weather conditions in the morning and update the entry with the work conducted throughout the day. Changes in weather throughout the day would often be recored, but it is not certain that all such changes were documented. A common problem with historical document is that events in the night would not be observed. Hill Carter often observed that there had been rain in the night (such details can be found in the narrative variable of the database, as seen in table 5). However, is not clear how often this occurred without him observing and documenting it. The descriptions themselves are often subjective as well. A pleasant day in winter most probably has different temperature conditions than a summer day that was described as pleasant.

We also need to be careful when applying the methods to other historical documents. Agricultural practices varied across space. While these labor rotations were common in the Deep South (states like Mississippi, Louisiana, and Alabama), this was not universally true (Toman, 2002). Locations at lower latitudes and elevations in much of the cotton belt had higher temperatures then other parts of the United States. There were colder temperatures in places such as the Upper South (states like Virginia, the Carolinas, and Tennessee), where the Shirley Plantation was located. Cotton plants required higher minimum temperatures than many other crops. This meant cotton grew at a much slower rate and was harvested later in cooler areas. The result was the phenophases of cotton and corn did not synchronize as well in the Upper South as they did in the Lower South. Corn might end up being the prioritized crop and be weeded first. A failed planting of cotton might result in a late replanting, further throwing off the timing between the different crops – as happened to the cotton on Shirley Plantation in May of 1822 and 1823. These factors will make a particular analysis more complex. On the other hand, these factors can help improve our understanding of the range in responses crops have to weather conditions.

Further, how these document were kept can vary across space and time. The way Americans kept these document may have been very different from other former British colonies. What was deemed important to creditors could also influence this. If an area was more likely to be financed by British banks than American, then there could be more similarities between American cotton plantations and British sugar plantations, than with tobacco plantations in the Upper South. Different imperial metropols could have different expectations as well. The French Empire could have different standards and practices compared to the British, Spanish, or others. Further complicating and enmeshing these systems was the transfer of territory. What became the Louisiana purchase changed hands between the French and Spanish several times before becoming an American territory. This resulted in the document being in French, Spanish, and English, and having influences from the French, Spanish, British, and American systems (Baptist, 2014; Beckert, 2015; Tadman, 2000). While any analysis conducted using these documents needs to keep the limitations in mind, they do not negate the value of these documents.

Future work will focus on expanding the database in time and space, while also expanding the methods available for its analysis. Additional years at Shirley Plantation will be added to the available data. Documents from additional plantations in Virginia will be analyzed as well. Temperatures will then be reconstructed using the response of various species to prevailing weather conditions. This can then be used to create a "phenochronology," similar to dendrochronology, but using historical phenological observations of plants similar to what Aono and Kazui (2008) have done with cherry blossoms, and what Chuine et al. (2004) have done with grape harvests. Further the availability of entries for several different species (Figure 2) can be combined to refine reconstructions and fill gaps in the document for individual species.

Author contributions. GB, JE, and RD designed the study; GB, JW, OL, SD extracted the data and built the database; GB and JE analyzed the data; GB wrote the initial draft; and all authors contributed to writing and editing.

Competing interests. The authors declare that they have no conflict of interest.

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Figure 1. Map of Tidewater Virginia. Shirley Plantation is located along the James River, 20 kilometers (12 mi) southeast of the weather station at Richmond International Airport. The inset includes the political boundaries in Virginia during the period of 1816-1842.

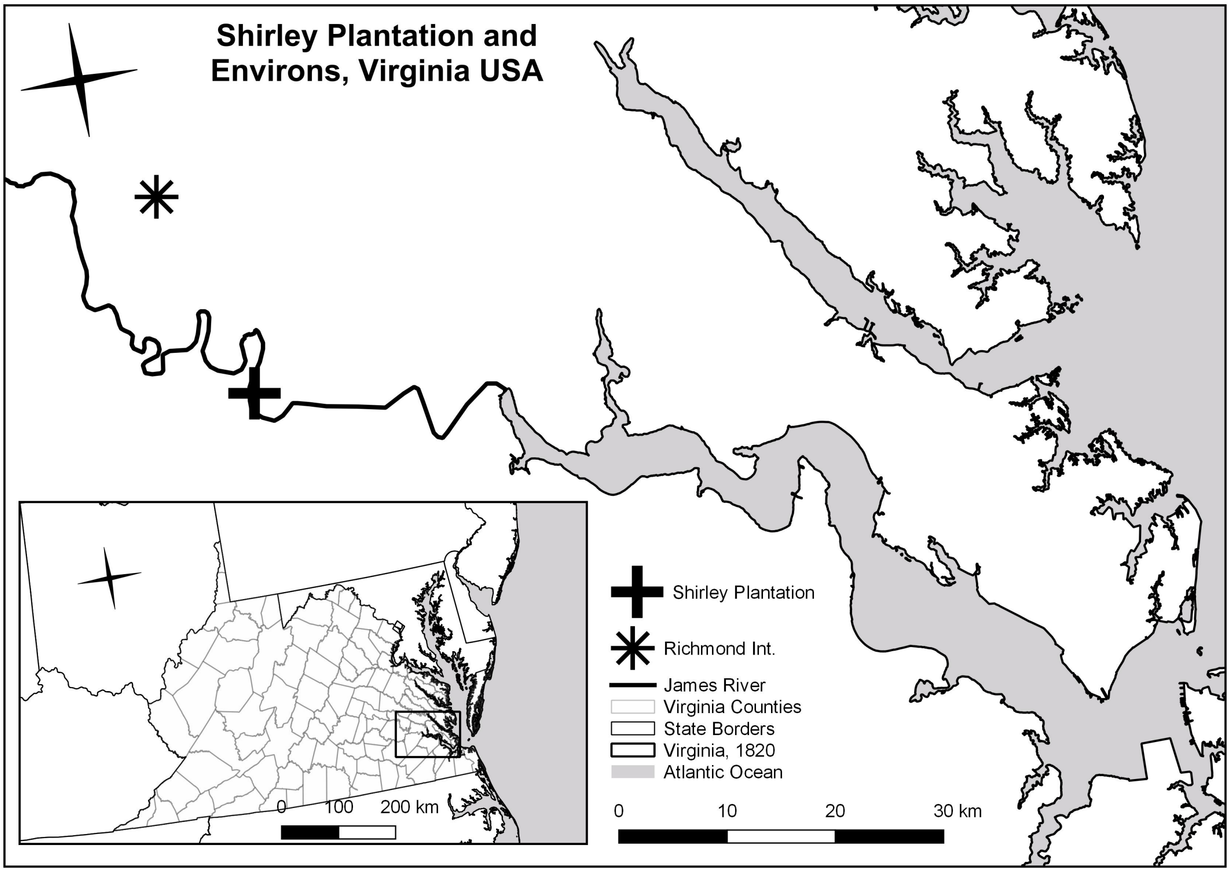

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Figure 2. Heat map of species mentioned in the Shirley Plantation document. This heat map shows which years a crop was mentioned, and how many times it was mentioned that year.

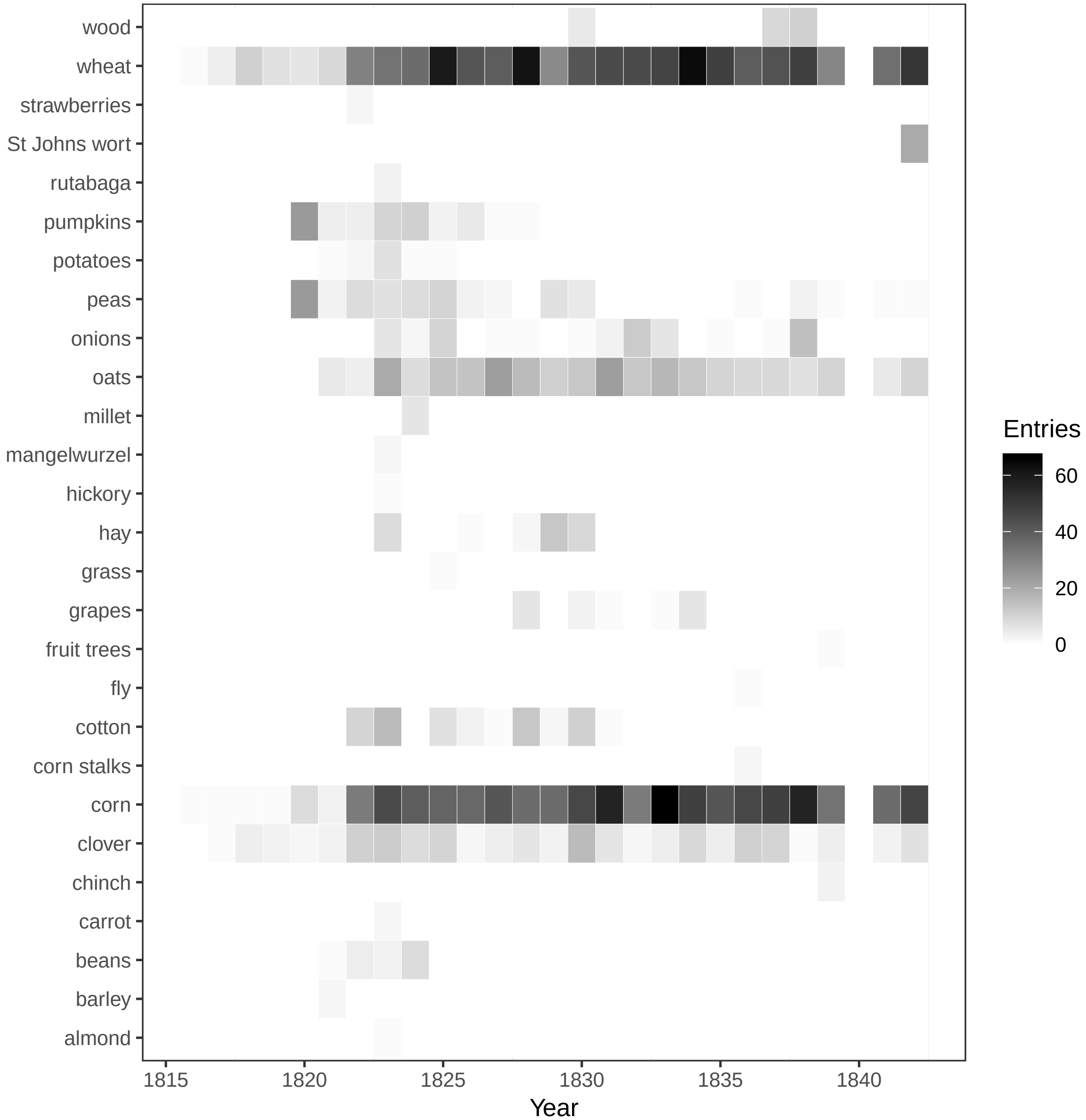

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Figure 3. Number of database entries in non-overlapping 30-day periods extracted from the Shirley Plantation document.

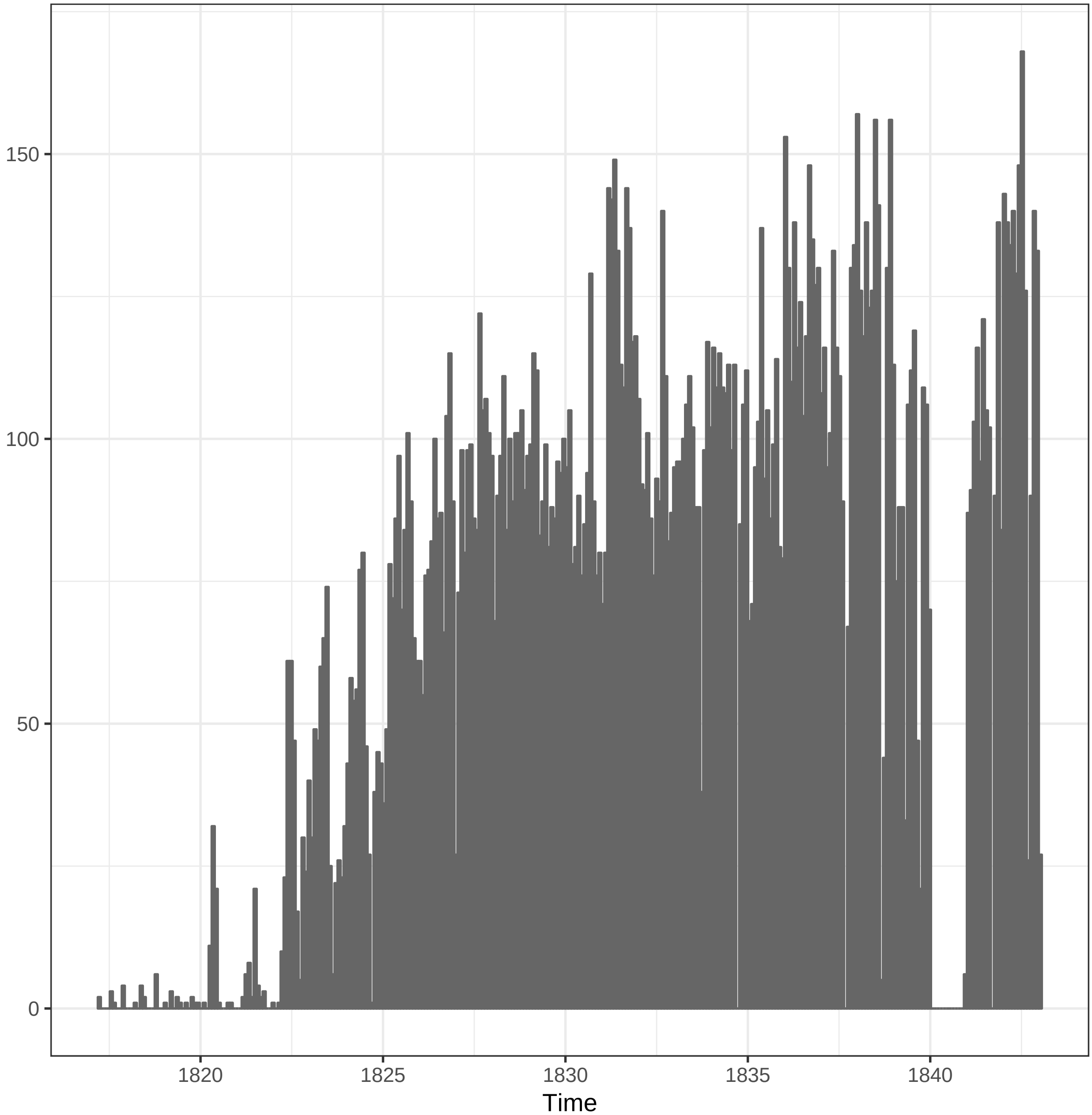

Figure 4. Number of database entries month. Activity on the plantation increased over the growing season, and then diminished over the fall and winter.

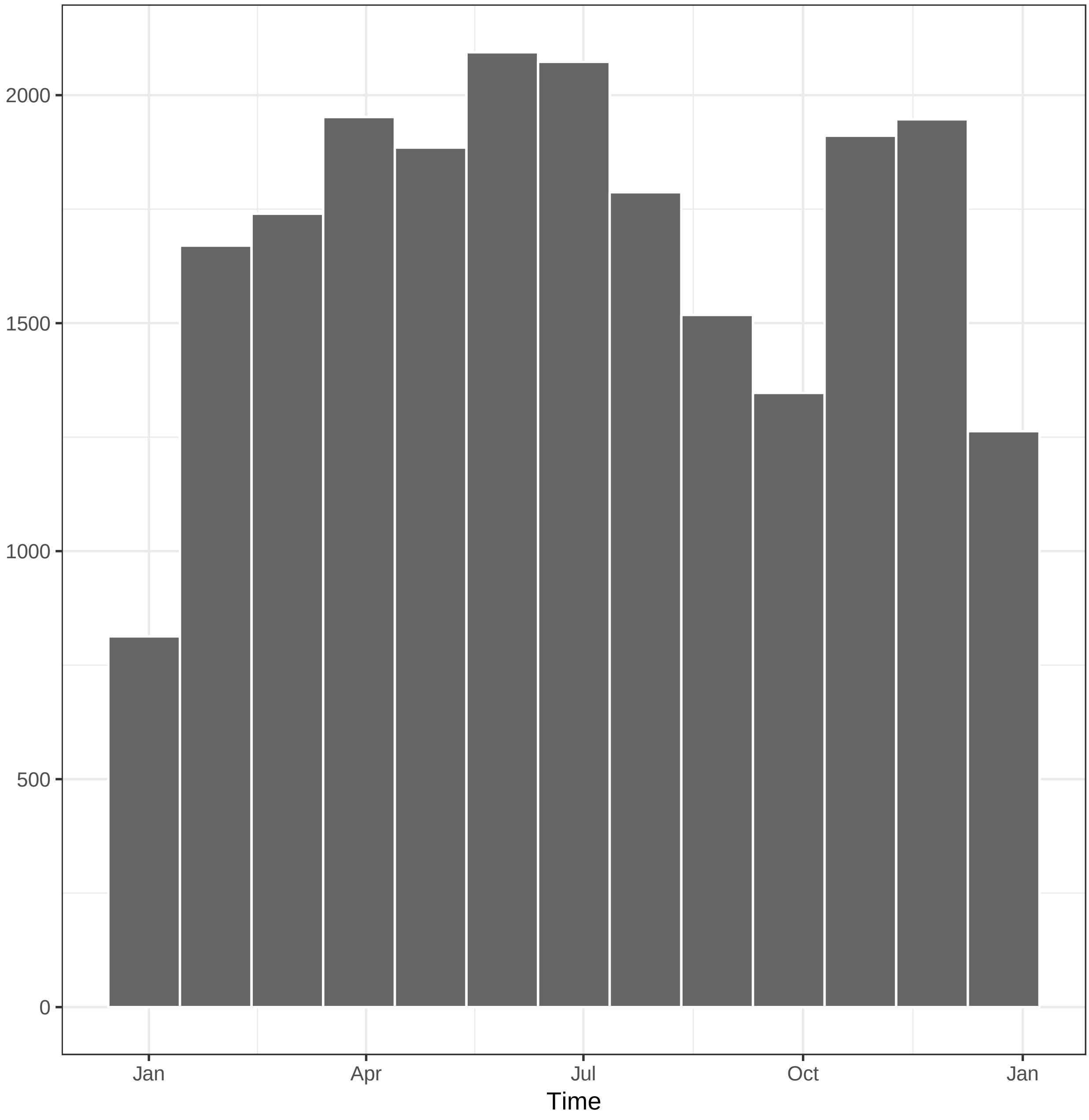

Figure 5. Entry type by observation category. The most common entry was about the weather, followed by agriculture, operations, and labor. Other categories had many fewer observations.

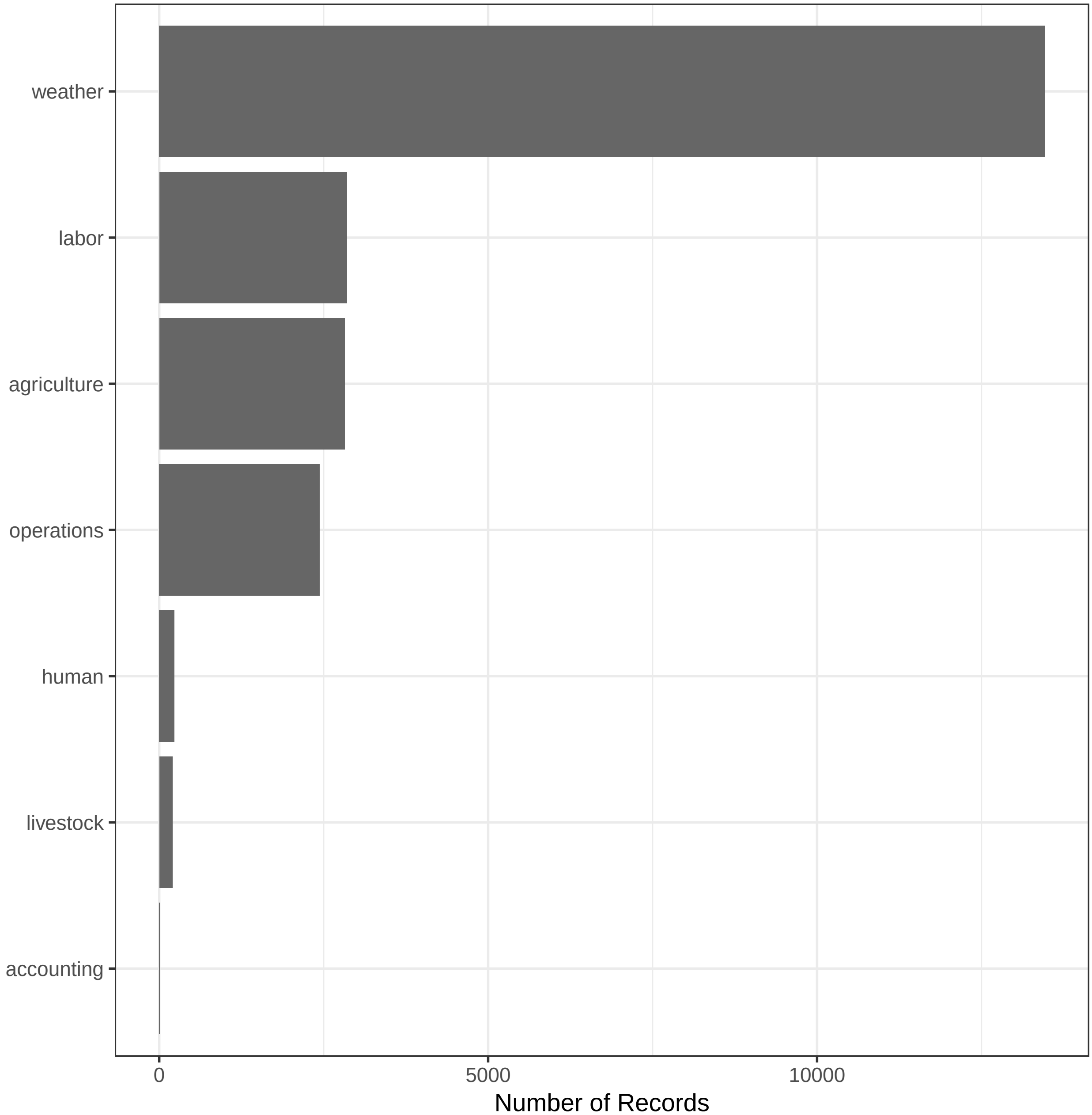

Figure 6. Histogram of last spring freeze days. This figure shows the distribution of last spring freeze days in Richmond, Virginia from 1942–2017. The black vertical line shows the median last spring freeze events in the data extracted from the Shirley Plantation document covering the period 1822–1838. There was one year where where no freeze events were documented for the spring. This leaves 16 years in the historical set.

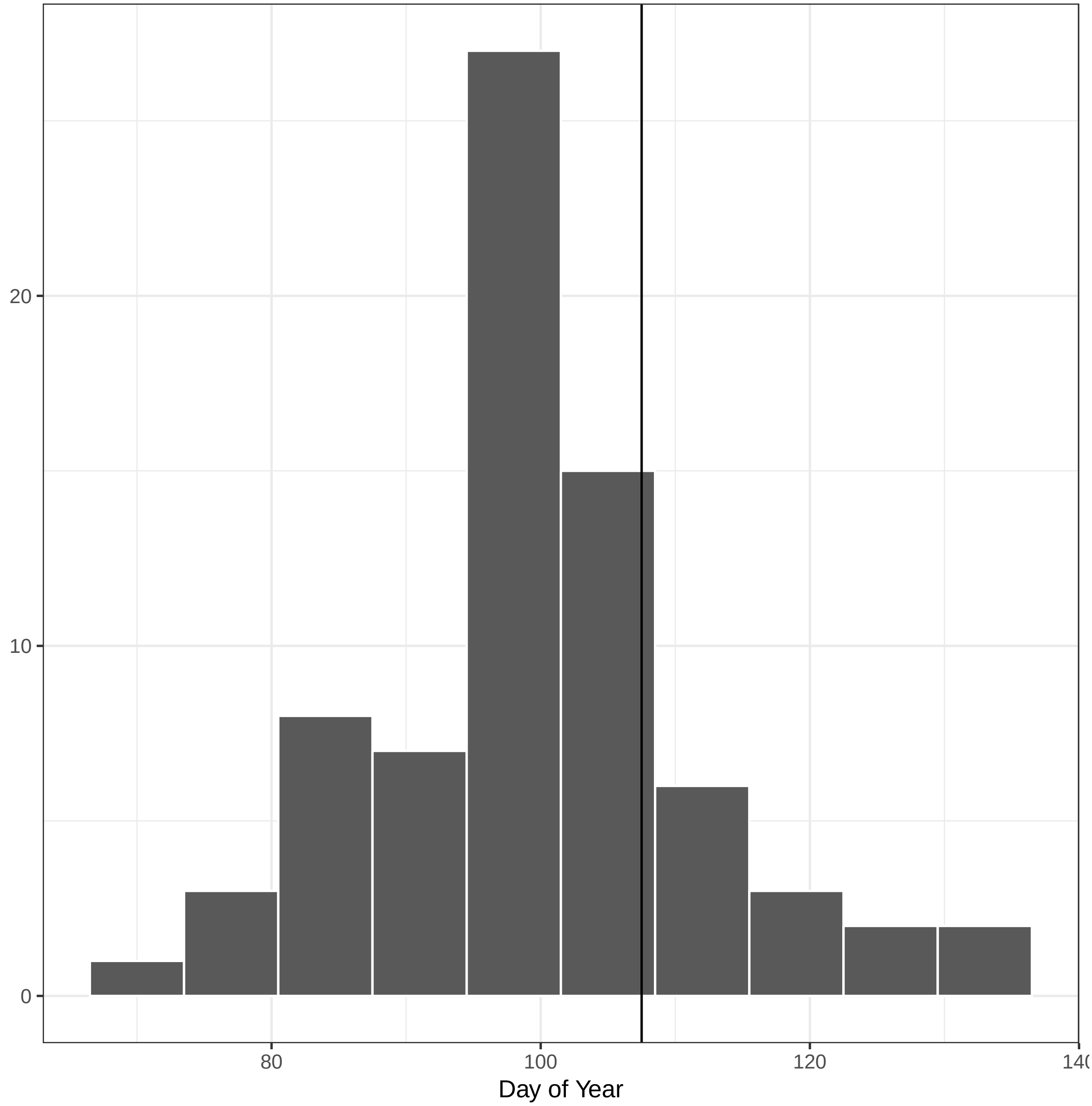

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Figure 7. Reports of ague and fever in the Shirley Plantation document during the period 1823–1842. Data for 1839–841 has not been generated yet. There are two decades of data, minus the missing years. Onset of symptoms indicate that the mean daily temperatures had been above 18° Celsius (64.4° Fahrenheit) long enough for the sporological cycle of *Plasmodium* to complete in the host *Anopheles* mosquito.

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Figure 8. Histogram of expected first malaria symptoms in Richmond, Virginia using data from 1942–2017. The black vertical line shows the median first malaria symptom reports in the data extracted from the Shirley Plantation document covering the period 1822–1838.

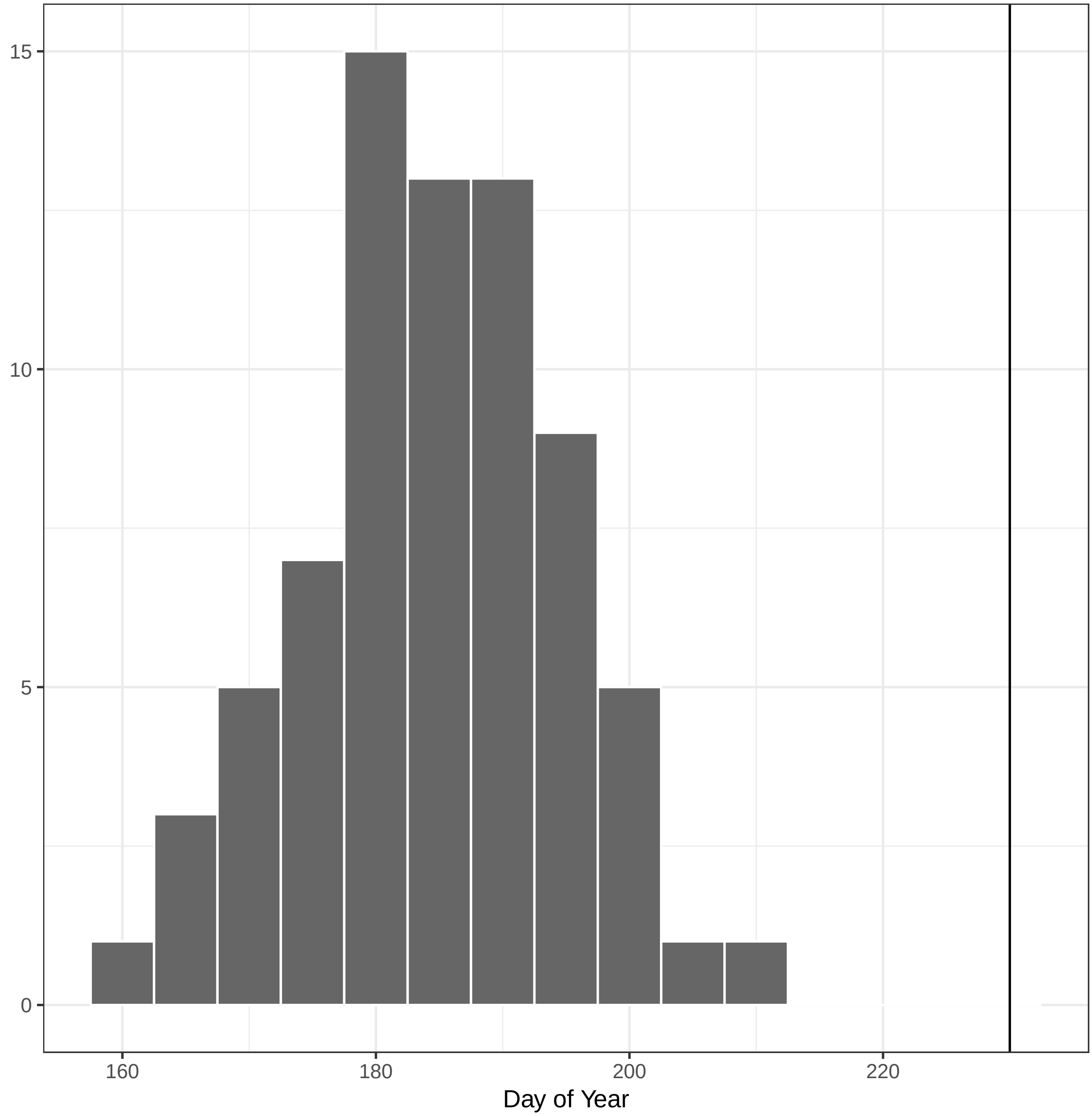

Table 1. Observation type and subcategories used in the Shirley Plantation document.

Accounting	Agriculture	Human	Labor	Livestock	Operations	Weather
selling	experimenting	health	carpentry	fattening	burning	hydrology
	harvesting	holiday	constructing	feeding	clearing	precipitation
	pest	problem	delivering	fixing	dragging	problem
	phenology	runaway	general	health	drying	smokey
	problem		hauling	managing	fallowing	temperature
	replanting		preserving	moving	ginning	thundering
	sowing		repairing	problem	hoeing	wind conditions
	thinning		traveling	shearing	hydrology	
	weeding				landscaping	
					penning	
					plowing	
					problem	
					shelling	
					treating	

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Table 2. Archaic terms encountered in the Shirley Plantation document.

Term	Definition
ague	an archaic term for illness that is now typically diagnosed as malaria
bauks	strip of land where corn is planted
bilious fever	an archaic term for illness that is now typically diagnosed as malaria. Believed to be caused by an imballances of the bile tempers of early western medicine
chinch	a pest insect species
cockle	a type of nematode that infects wheat
distemper	term for an illness believed to be caused by an imbalance of the four tempers
laying off	setting up drainage on a terraced field
listing	a partially mortared wall with turf on top
lodging	stalk collapse, esp. corn and wheat
marl	lime stone baked in kilns that is then crushed and spread on fields to decrease the acidity of the soil, similar to liming and plastering
rust	a fungal crop pest
stob	fence post
windrowing	cutting a row of hay or small grain

Table 3. Terms with similar meanings and spellings.

Term	Alternate term 1	Alternate term 2	Alternate term 3
ague and bilious fever	distemper	bilious fever	tertian fever
bauks	balk	baulk	
beveling	bavelling	bavel	laveling
chinch	cunch	conc	conch
cows	beef	beeves	bovines
harvesting	cutting	onioning	picking
hauling	moving	getting up	getting off
knocked down	blown over	prostrated	blown over
shelling	cobing	seeding	beating

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Table 4. Cultivars found in the Shirley Plantation document.

Species	**Cultivar**									
clover	pug									
corn	hominy	gourdseed	shell	white	yellow					
grapes	blue	orchard								
peas	partridge	cowpeas	galavant							
wheat	white may	purple straw	red bearded	lloyd	red	turkey	rock	red may	domoville	

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Table 5. Example of the database extracted from the Shirley Plantation document covering the period July 1–7, 1838.

Date	Observation Type	Observation	Species	Cultivar	Narrative	Categorical	Numerical
7/1/1838	weather	cloud conditions				clear	
7/1/1838	weather	temperature				hot	
7/1/1838	weather	cloud conditions				thundering	
7/1/1838	weather	precipitation				rain	
7/1/1838	operations	shelling	wheat			shelling	
7/2/1838	weather	precipitation				rain	
7/2/1838	weather	temperature			to excess	hot	
7/2/1838	agriculture	harvesting	wheat	purple straw		harvesting	
7/2/1838	operations	shelling	wheat			shelling	
7/2/1838	agriculture	problem	wheat			ripe	
7/2/1838	agriculture	problem	wheat			tangled	
7/3/1838	weather	temperature				Fahrenheit	87
7/3/1838	weather	cloud conditions				clear	
7/3/1838	weather	temperature			to excess	hot	
7/3/1838	agriculture	phenology	wheat			opening	
7/3/1838	operations	shelling	wheat			shelling	
7/3/1838	operations	problem	wheat		windrows	sprouting	
7/3/1838	agriculture	problem	wheat		destroyed by hurricane	lost	
7/4/1838	weather	temperature				Fahrenheit	90
7/4/1838	weather	cloud conditions				clear	
7/4/1838	weather	temperature			hottest day this summer	hot	
7/4/1838	weather	cloud conditions			several	thundering	
7/4/1838	agriculture	harvesting	wheat			harvesting	
7/4/1838	operations	shelling	wheat			shelling	
7/4/1838	agriculture	problem	wheat			too ripe	
7/5/1838	weather	temperature			hotter than yesterday	hot	
7/5/1838	agriculture	harvesting	wheat	purple straw		harvesting	
7/5/1838	weather	temperature				Fahrenheit	92
7/6/1838	weather	cloud conditions				cloudy	
7/6/1838	weather	temperature			great change	cool	
7/6/1838	weather	wind conditions				windy	
7/7/1838	agriculture	harvesting	wheat	purple straw		harvesting	
7/7/1838	weather	cloud conditions				clear	
7/7/1838	weather	temperature				warm	
7/7/1838	agriculture	harvesting	wheat	purple straw		harvesting	