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In the ruins: the neglected link between archaeology and weed science

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Review

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Abstract

The aim of this paper is to bring attention to weed ecology research that is taking place in an unexpected discipline: archaeology. While archaeobotanists (archaeologists or botanists who specialize in archaeological plant remains) have been accessing literature in weed ecology for decades and applying the findings to their own studies, their results are almost exclusively published in archaeological journals such as the *Journal of Archaeological Science* or *Vegetation History and Archaeobotany*. For this reason, their work is underutilized by weed ecologists, especially those who have an interest in historical weed ecology. Archaeobotanical research could help weed scientists understand the long-term effects of agricultural practices on weed communities and predict the potential impacts of climate change. This paper begins with a brief review of the history of archaeobotany as a discipline, then describes ways in which weed ecology is applied in archaeobotany, including Functional Interpretation of Botanical Surveys (FIBS). Finally, we present opportunities for future collaboration between archaeobotanists and weed scientists.

Introduction

This paper considers intersections between the disciplines of archaeobotany and weed ecology. Archaeobotany, the study of archaeological plant remains, is performed by both archaeologists and botanists. Plant remains are preserved through processes such as waterlogging, desiccation, and charring and recovered during archaeological excavations. Seeds from weedy species are often found among the remains of economic plants such as cereals. When weed seeds are present in archaeological samples, archaeobotanists can use insights from weed ecology (the study of how weeds interact with their biotic and abiotic environments) to better understand the agricultural systems from which they came. This approach has led to breakthroughs in archaeological understandings of agricultural practices such as irrigation (Charles et al. 2003), crop rotation (Bogaard et al. 1999), and fertility management (Neveu et al. 2021). In particular, the Functional Interpretation of Botanical Surveys (FIBS) approach has expanded the study of weeds in archaeology (Charles et al. 1997). FIBS uses functional traits (such as canopy height or germination time) rather than species identities to describe how agricultural practices shape weed communities. Archaeobotanists using the FIBS approach apply functional insights from modern weed ecology to archaeological weed remains.

We suggest that the FIBS approach to archaeological weed studies is relevant not only to archaeologists studying ancient agriculture but also to modern-day weed scientists with an interest in historical weed ecology. For example, FIBS may illuminate the long-term effects of agricultural regimes on plant communities or provide insight into weed responses to climate change. This review seeks to (1) summarize the history of archaeobotany and its relationship with weed ecology, (2) explain how FIBS enables archaeobotanists to identify ancient agricultural practices, and (3) highlight opportunities for future collaboration between archaeobotanists and weed scientists.

Background

Archaeobotany, a term interchangeable with paleoethnobotany, began in the 19th century as an intersection between botany and archaeology. Unlike paleobotany, archaeobotany is focused on human–plant interactions rather than the evolution of plants. Possibly the earliest example of what might be called archaeobotanical research was conducted in 1826, when botanist Carl Sigismund Kunth studied the plant remains from the tombs at Deir el-Bahri along the Nile (Stuart 2018). In the 1860s, Oswald Heer demonstrated the survival of waterlogged plant remains from a Swiss lake (Stuart 2018). These two studies were crucial in showing that plant remains could survive in archaeological contexts, and more studies followed. Interest in the

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Table 1. Examples of plant remains recovered from archaeological sites.

Archaeological context	Source of plant remains	Deposition type
Buried soil horizon/cultivation layer	Remains from stubble burning, remains of household waste used as fertilizer	Primary and secondary deposition
Grain-drying oven	Remains of processed cereals	Primary deposition
House floor	Remains of stored crops, remains from ash spread on floors	Secondary deposition

discipline grew slowly, but by the 1960s, archaeobotanical research had become commonplace (Pearsall 2019). Funding through the U.S. National Science Foundation (NSF) for archaeobotanical studies peaked in the 1990s (Marston et al. 2015: 10), but archaeobotany continues to be a thriving and growing discipline with five NSF Doctoral Dissertation Research Improvement grants in 2021 utilizing archaeobotanical methodologies. While this article focuses primarily on macroremains (specifically weed seeds) that can be seen with the human eye, archaeobotany also encompasses the study of microremains such as phytoliths, starches, and pollen. There is an increasing interest in the archaeobotany community in collaborating with other plant ecologists and landscape specialists on research topics of mutual interest (de Vareilles et al. 2021).

The aim of archaeobotany is to better understand human–plant relationships in the past and illuminate ancient human behaviors (Wright 2010). Human actions such as harvesting, crop processing, and cooking result in the deposition of plant remains into the archaeological record. These plant remains are then collected by archaeologists from contexts in archaeological sites, such as pits, middens, and floor surfaces. Archaeologists distinguish between “primary” deposition, in which remains are deposited at the location where they were used, and “secondary” deposition, in which the location of the deposit is not the location where the remains were used (Schiffer 1972). Table 1 illustrates some examples of primary and secondary deposition. Understanding how plants became part of the archaeological record is key to making accurate interpretations based on the data (van der Veen 2007).

Weed flora in archaeobotanical samples have been the subject of study for decades (Knörzer 1979; Wasylikowa 1981). Historical weed flora are often quite different from those found in present-day cultivated fields. Modern weed research can help archaeobotanists interpret weed flora from the past by providing rich data sets on weed species responses to specific abiotic and biotic factors or management regimes. The development of archaeobotany is tied to the development of processual archaeology in the 1950s and 1960s, also known as “New Archaeology,” which emphasized empirical data sets and quantitative methods over the previous cultural–historical approach (Binford 1989). Findings from weed ecological research began to have a significant impact on archaeobotanical studies in the 1960s and 1970s with the increasing implementation of flotation techniques for seed recovery, a method suggested by the botanist Hugh Cutler (Struever 1968). Using flotation, soil samples (usually at least 1 L in size, often 10 to 30 L) are placed in a fine mesh (usually 500 μm) and submerged in water (see Figure 1). When agitated, the soil falls through the mesh. Stones, bones, and other artifacts are left behind in the mesh. Lightweight objects such as snail shells and charred seeds float to the top of the water and are caught in a finer mesh sieve (usually 250 or 300 μm; see Figure 2). This “light fraction” is carefully dried and then sorted with the use of a microscope. The benefit of flotation is that it allows seeds to be recovered even when they are not noticed by excavators, allowing for the recovery of small weed seeds that would be otherwise overlooked. As smaller weed seeds began to be recovered in greater numbers with flotation, archaeobotanists began to study them in greater detail.

Figure 1. Example of a flotation setup from Bamburgh Research Project, July 2019. The mesh is placed in the wooden tank and water is recirculated through two black settling tanks.

Weed ecology can only be applied in archaeological research if weed species can be identified. Several factors may limit weed identification. First, flotation has not been used equally by archaeologists in all parts of the world. Generally, flotation requires access to running water or the ability to store and transport bulk soil samples to a location where they can be processed, as well as time and labor to process the samples. Not all projects are able to fulfill these requirements. This disparity has affected the regions where weed ecology can be applied to archaeological research, with a heavy bias toward Europe and the Near East. An additional barrier stems from the lack of region-specific weed identification manuals for some areas. For example, the lack of weed manuals for southeast Asia hinders the identification of weed seeds even when they can be recovered (Rahman et al. 2020). Finally, weed seeds do not always become part of the archaeological record. Weed seeds were harvested along with crops and accidentally charred through a variety of processes, such as in crop-drying ovens. Some cropping systems are much more likely to produce archaeological traces of weed seeds than others. For example, small weed seeds (e.g., *Chenopodium* spp. and *Amaranthus* spp.) are far more likely to be accidentally trapped in a cereal harvest than in a squash (*Cucurbita maxima* Duchesne) harvest. This difference creates a bias toward the archaeobotanical study of weeds in cereal-cropping systems.

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Figure 2. Image of light fraction in a fine mesh sieve bag.

Historically, weed ecological research in archaeobotany (like ecological research in general) could be divided into two approaches: the autecological approach and the synecological approach. Autecology focused on the behavior of individual species. Synecology, also referred to as phytosociology, focused on plant communities as a whole. Using the presence or absence of key diagnostic species known to have narrow ecological ranges, archaeobotanists would be able to interpret entire weed communities to make inferences about the environments in which these communities might have been formed. For a more detailed discussion of the differences between these two approaches, see van der Veen (1992).

In the late 1990s, Charles et al. (1997) introduced a third way to apply weed ecology in archaeobotany: Functional Interpretation of Botanical Surveys, or FIBS. The underlying assumption of this approach is that species that tolerate certain ecological factors often share a suite of common adaptive characteristics, referred to as a "functional type." By considering these functional types rather than specific species, FIBS makes it easier to compare archaeological samples for which different species may be present and different agricultural practices may have been in use. This approach relies heavily on multivariate statistics, primarily discriminant analysis and correspondence analysis (Charles et al. 1997). FIBS has become one of the dominant methods of applying weed ecology to archaeobotany (Jones et al. 2010). The development of this method has been supported by the increasing prevalence of functional approaches in present-day weed science (Bàrberi et al. 2018; Gaba et al. 2014; Jones et al. 2010; Navas 2012; Neve et al. 2018). Examples of FIBS in archaeobotany will appear throughout this review.

Practical Applications of Weed Ecology in Archaeobotany

Weed ecological information has several practical applications in archaeobotanical research, particularly research on agriculture. For example, weed seeds in archaeobotanical samples can be used to investigate the provenance of cereals. Weed seeds can also provide insight into the practices used in past cropping systems, enabling archaeobotanists to answer questions such as "Was this system irrigated or rainfed?" Other practices that can be investigated through weed ecological approaches include crop rotation, sowing time, manuring, disturbance, and weed management. More broadly, weed ecological approaches can be used to explore questions about the long-term, landscape-level effects of agricultural systems, including effects occurring in the context of climate change.

The use of weed ecological information represents an exciting avenue for further research into cropping systems of the past. This research has the potential to illuminate ancient practices and might also identify localized approaches that can be adapted for the present day. In the following sections, we outline the primary uses of weed ecological knowledge in the field of archaeobotany and suggest future directions for the field.

Provenance

Cereals found at archaeological sites were not always grown near the sites. This distinction is particularly important for higher-status sites whose residents could afford to import cereals from elsewhere. Weed ecology offers a method for identifying the origins of cereal remains found at these sites (Jones 1984). Lodwick (2018) used correspondence analysis on weed seeds associated with spelt (*Triticum spelta* L.) from southern England in the Iron Age to explore the geographic origin of the spelt. The author argued that the weed species could be separated into groups based on soil requirements, such as their affinity for calcareous soils. Samples containing many weed seeds from a particular group likely originated from an area with soils appropriate for that group of weeds. Weed species used in this analysis included corn chamomile (*Anthemis arvensis* L.), henbane (*Hyoscyamus niger* L.), and prickly poppy (*Papaver argemone* L.). Applying this approach does require a significant amount of prior work in understanding the ranges of different weed species and soil characteristics of the surrounding areas but is potentially quite promising in regions like the United Kingdom where such background data are readily available. If combined with other methods, such as strontium stable isotope analysis of cereals (Bogaard et al. 2014; Styring et al. 2019), this approach could help archaeologists understand cereal-based agricultural networks that supported large settlements in various geographic regions.

Crop Rotation

Crop rotation (sequentially growing different crops on the same land) and fallowing (leaving the land to "rest" for a period of time) regimes can have an enormous impact on agricultural productivity and sustainability (Magdoff and van Es 2021; Palmer 1998a, 1998b; Sumner 1982). Understanding the spatial and temporal distribution of crops can help researchers understand risk management in past agricultural systems (Marston 2017). Crop rotation systems cannot necessarily be inferred from the crop species composition of archaeological samples containing mixed species (e.g., a sample containing both cereals and pulse crops), because mixing can occur through a variety of processes, including postdepositional

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mixing or mixing during various processing stages (Jones and Halstead 1995).

Weed ecological knowledge provides a window into crop rotation systems of the past, because crop sequences impact weed seedbank composition (Bohan et al. 2011). For example, Bogaard et al. (1999) identified 14 functional attributes related to the duration of the growth period, ability to regenerate under high disturbance, and drought resistance. These functional attributes were used to study how weed communities responded to various crop rotation and fallowing systems. The authors found that attributes related to high productivity (i.e., tall, broad canopies; low dry matter content; thick, wide leaves) were associated with rotation regimes including a legume crop. Later studies have interpreted archaeobotanical data based on this association. For example, the abundance of thin-leaved species such as common corncockle (*Agrostemma githago* L.), false thorow-wax (*Bupleurum lancifolium* Hornem.), and darnel (*Lolium temulentum* L.) could reflect a lack of crop rotation in the Roman and Visigothic periods at a site in the northeastern Iberian Peninsula (Colominas et al. 2019). In a different study, Neveu et al. (2021) suggest that an increase in perennial weeds and grassland plants during the Iron Age in northwestern France could be explained by crop rotation involving pasturing. Although recovered weed seeds do not provide definite information about crop rotations, weed ecology can be combined with other methods to reconstruct ancient cropping systems. As weed scientists continue to identify rotation effects on weed community composition, these insights may provide archaeobotanists with new ways to interpret weed seed assemblages.

Sowing Time

A fixed crop-sowing time is one of the earliest signs of agricultural adaptation (Hillman 1981). Storing seeds properly will prevent them from germinating until farmers trigger germination by providing suitable conditions (e.g., planting the seeds). For example, wild emmer [*Triticum turgidum* ssp. *dicoccoides* (Asch. & Graebn.) Thell.] naturally germinates in autumn; storing and planting the seeds for spring germination is an example of agricultural adaptation (Hillman 1981). During later transformations of regional agriculture, changes in crop-sowing time accompanied influxes of new crop species. For example, an influx of bread wheat (*Triticum aestivum* L.) occurred in Britain in the first millennium Common Era (CE) under Roman rule (Jones 1981). Many of these newly introduced crop species that became dietary staples could be sown in multiple seasons. Others were more successful in a particular season or under particular climatic conditions. Understanding variation in crop-sowing times offers insight into how humans adapt agricultural strategies over time while simultaneously creating a framework into which we can add other agricultural activities, such as harvesting and crop processing. Finally, identifying the season in which a crop was sown can improve the accuracy of radiocarbon dating because radiocarbon levels fluctuate throughout the year (Manning et al. 2018).

Archaeobotanists have been trying for decades to use the presence of weed flora to determine crop-sowing times. Bogaard et al. (2001) demonstrated through correspondence analysis that crop-sowing time has a significant impact on the composition of weed flora. The authors also used correspondence and discriminant analyses (the FIBS approach) to understand the relationship between crop-sowing time and weed functional attributes related to seasonality, regeneration following disturbance, the quality of the growth period (largely indicative of soil fertility), and shade tolerance. A discriminant analysis using functional attributes as discriminant variables achieved 97% success in correctly classifying weed groups according to crop-sowing time (spring or autumn). This analysis used previously published data (Hofmeister 1991, 1992, 1996; Hüppe and Hofmeister 1990) on cereals, including bread wheat and root/row crops in 20th-century Germany. Functional attributes were also used to classify weed groups according to crop-sowing time in an experimental trial in northwest Spain with glume wheat (largely spelt; Charles et al. 2002). The successful use of this approach (using weed ecology to infer crop-sowing time) in different regions and cropping systems suggests that the approach may be broadly applicable in archaeological contexts. Crop-sowing time is also a topic of interest to weed scientists. For example, a study by Gunton et al. (2011) on weed communities in arable fields across France found that crop-sowing time was strongly related to weed traits, including Raunkiaer life form, germination time, and flowering time.

One concern about using weed seeds to determine crop-sowing time is that crop-processing practices introduce systematic bias against spring-sowing indicators through sieving (Bogaard et al. 2005). Weed species associated with autumn crop sowing often have larger seeds than weed species associated with spring crop sowing (Bogaard et al. 2005). Fine sieving tends to favor larger weed seeds in the products (smaller weed seeds fall through the sieve and become by-products; Figure 3). Consequently, fine sieving may cause weed seed assemblages associated with spring-sown crops to mimic weed seed assemblages associated with autumn-sown crops (Bogaard et al. 2005). It is possible to limit this bias by focusing on samples at an early stage of crop processing that have not yet been sieved. The stage of crop processing can be determined through discriminant analyses focused on the amounts of grain, chaff, and weed seeds present in a sample (Jones 1992; McKerracher 2019). Crop-processing actions such as threshing, sieving, and hand sorting remove some weed seeds more efficiently than others due to differences in seed size and morphology (Figure 3). For this reason, the types of weed seeds found in a sample are a reliable indicator of crop-processing stage (Jones 1987).

McKerracher (2019) identified the crop-processing stages of samples from early medieval England, then used discriminant analysis and correspondence analysis to investigate crop-sowing times. The correspondence analysis was based on weed species such as *A. githago*, common lambsquarters (*Chenopodium album* L.), and catchweed bedstraw (*Galium aparine* L.). Because crop processing biases weed seed assemblages toward indicators of autumn sowing, results that appear to reflect spring sowing can be interpreted with more confidence than results that appear to reflect autumn sowing. In a similar study from Neolithic Iberia, Antolín et al. (2015) found indicators of spring sowing, including saltbush (*Atriplex patula* L. or *Atriplex prostrata* Bouchér ex DC.), *C. album*, and heliotrope (*Heliotropium europaeum* L.).

Irrigation

Irrigation is one of the primary methods that past (and modern-day) societies have used to intensify agricultural production and extend arable land into marginal arid regions. Identifying the presence of irrigation archaeologically can be a challenge, however. Jones et al. (1995) studied contemporary cropping systems in Borja, Spain, where the primary difference between the fields was dry farming versus the use of various forms of irrigation. This study did not use the FIBS methodology, but rather relied

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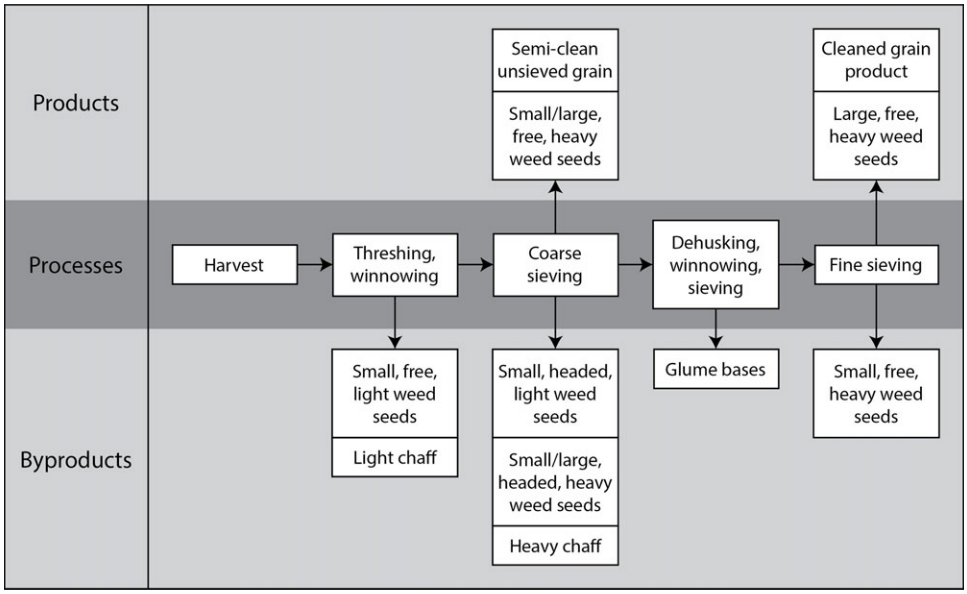

Figure 3. Stages of cereal crop processing with their products (grain and weed seeds) and by-products (chaff and weed seeds). Adapted from McKerracher (2013) and Jones (1984).

on two phytosociological associations identified by Braun-Blanquet and de Bolós (1957): the Roemerieta-Hypecoetum penduli (associated with rainfed winter cereals) and the Atripliceto-Silenetum rubellae (associated with irrigated winter cereals). The authors found that these different phytosociological associations differed between fields, with the strongest difference between intensely and moderately irrigated fields (rather than between irrigated and dry fields).

Charles et al. (1997) applied the FIBS methodology to the data from Jones et al. (1995). By using the FIBS methodology, the authors were able to reach more general conclusions about how irrigation affects weed communities that could be applied to archaeological case studies in other regions. For example, weed species in irrigated fields tended to have higher specific leaf areas and taller canopies (Charles et al. 1997). Charles et al. (2003) demonstrated the use of the FIBS methodology to identify differences between rainfed and irrigated agriculture in Jordan.

Other archaeobotanists have taken different approaches to identifying irrigation levels from the weed seeds in samples. For example, Marston (2017) investigated the presence or absence of seeds from weed species known to thrive in wetter conditions, such as sedges (family Cyperaceae), at Gordion (an archaeological site 70 km southwest of Ankara, Turkey). When this author noted a significant increase in the number of sedges in the Roman phase of occupation, he linked it to the increase in bread wheat production and suggested that the combination of these factors indicated an increase in irrigation. Another example comes from Iron Age Thailand, where Castillo (2011) found a high co-occurrence of rice (*Oryza sativa* L.) with paracress [*Spilanthes acmella* (L.) L.], a common weed of dryland rice cultivation. This finding suggested that the rice had been grown under rainfed conditions rather than in irrigated fields.

Soil Fertility

A recently developed use of weed ecological information in archaeobotany concerns the identification of manuring practices and fertility management. The nutrient requirements of many weed species are already known, largely because weed scientists have studied responses to fertility in their efforts to understand weed–crop competition (Little et al. 2021). Neveu et al. (2021) used known nitrogen and pH requirements for weed species (such as wild carrot [*Daucus carota* L.], hawkweed oxtongue [*Picris hieracioides* L.], and hemp-nettle [*Galeopsis* spp.]) to better understand soil fertility and fertility management in the Bronze and Iron Ages in northwestern France. In this region and period, crops such as free-threshing wheats (*Triticum* spp.) would have depleted soil fertility if soil nutrients were not replenished. The low frequency of species linked to nitrogen-poor soils suggests that fertility did not decrease during the study period, perhaps because growers used the best land available and fertility management practices (Neveu et al. 2021). In these respects, Bronze Age and Iron Age agriculture in northwestern France may have borne some similarities to modern-day cereal-cropping systems.

More generally, historical soil health is an important and understudied topic in archaeology (Montgomery 2008). Most studies of historical soil health are conducted on buried soils using methods such as micromorphology, geochemical analysis, and stable isotope analysis (Bell and Boardman 1992). Weeds can also serve as indicators for some soil characteristics, including compaction and water availability as well as fertility (Mohler et al. 2021; Pätzold et al. 2020). Although less sensitive than the soil tests that can be performed on present-day soils, analyses of weed flora provide general information about historical soils. This information may help clarify how agricultural systems affect soils across long timescales (centuries). For example, Rösch (1998) used agricultural weeds from southwestern Germany to demonstrate increasing soil acidification over the course of thousands of years (Neolithic to present day).

Cultivation Intensity

Recently, functional weed ecology studies in archaeobotany have focused less on identifying specific strategies (crop rotation, sowing time, irrigation, etc.) and instead emphasized a more general approach of identifying “low-intensity” (extensive) versus

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"high-intensity" (intensive) agricultural strategies (Bogaard et al. 2016; Jones et al. 1999). The archaeobotanical definitions of these terms resemble typical agronomic definitions but focus on labor rather than capital inputs. In archaeobotany, intensity is defined as labor inputs per unit of land, with labor inputs being defined by the application of strategies such as irrigation, manuring, intensive weeding, or tillage (Bogaard et al. 2016, 2018).

An early study looking at disturbance and fertility in agricultural systems found that larger weed species (canopy size and leaf size) were found in systems with less disturbance and higher fertility (Jones et al. 2000). Disturbance and habit productivity (fertility and water availability) explain considerable variation in present-day weed communities (Jones et al. 2010; Légère et al. 2005). Conversely, variation among weed species assemblages from archaeobotanical samples can provide insight into the disturbance regimes and habitat productivity of past agricultural systems (Jones et al. 2010). This approach has been used in studies of Neolithic Ireland, Britain, and continental Europe to demonstrate that Neolithic farmers grew crops in fixed, long-term plots rather than practicing shifting cultivation (Bogaard and Jones 2007; McClatchie et al. 2014; Whitehouse et al. 2014).

Archaeobotanists may also use stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) of cereal crops to identify agricultural practices (irrigation and manuring, respectively) more clearly (Bogaard et al. 2007; Fraser et al. 2011; Styring et al. 2016; Wallace et al. 2013). For example, Aguilera et al. (2008) combined the study of weed seeds with the study of nitrogen and carbon isotope values in their analysis of a Neolithic site from Spain. Their study categorized weed species as "ruderal" or "cereal" weeds and found that ruderal weeds were associated with barley (*Hordeum vulgare* L.) cultivation, while cereal weeds were associated with wheat cultivation. The authors attribute these associations to barley's status as a secondary crop, relegated to more marginal areas, while wheat was confined to intensely cultivated fields. These archaeobotanical data, combined with $\delta^{15}N$ analysis of the cereals, suggest that increased competition with ruderal weeds led to a decrease in nitrogen availability for the barley and therefore a decrease in grain nitrogen content. Other researchers have performed stable isotope analyses on the archaeological remains of animals (e.g., livestock) to incorporate animal husbandry into their studies of low- versus high-intensity cultivation (Alagich et al. 2018; Styring et al. 2017).

Historical Weed Management

Archaeobotany offers a way to study the relationships between humans and weeds in the distant past. For example, samples from southwestern Germany suggested that *A. githago* became less prevalent in the early Medieval period because fields were intensively weeded (Rösch 1998). A 1,500-yr sequence of pollen samples from Northumberland (northern England) showed how management factors, including grazing intensity and burning, affected the species composition of a pastoral landscape (Davies and Dixon 2007). These data provided insight into the effects of management factors on species diversity and the balance between heather [*Calluna vulgaris* (L.) Hull] and other species. In the context of invasive species biology, archaeobotanical data from eastern France (Neolithic to present day) have been used to demonstrate relationships between management factors (e.g., tillage) and the prevalence of invasive species (Brun 2009).

These examples show that archaeobotanical data sets often cover very long timescales. For this reason, they can illuminate the long-term effects of weed management practices or the effects of weed management in agricultural systems that are not used in the modern world. Such knowledge could contribute to a broader understanding of weed ecology.

Ecological Diversity, Sustainability, and Climate Change

Weed ecological information can be used to assess long-term impacts of past agricultural regimes on the diversity of local flora. Ferrio et al. (2012) categorized weed species represented in the archaeological assemblage from Tell Halula, a Neolithic site in Syria, as "cereal weeds" (weeds often associated with cereal crops) and "other weeds." During the Neolithic era, weed community diversity decreased and the ratio of cereal weeds to other weeds increased. These changes were associated with agricultural intensification. An inverse association between weed community diversity and agricultural intensification is well established in the weed science literature (Carmona et al. 2020; José-María et al. 2010; Storkey et al. 2010). Further archaeobotanical evidence for agricultural intensification in the Neolithic has been found across Europe, such as the establishment of permanent fields rather than shifting cultivation in Germany, Britain, and Ireland (Bogaard 2002; McClatchie 2014; McClatchie et al. 2014).

More generally, archaeobotanists can use weed ecology to explore the sustainability of past food-production systems at a landscape scale. For example, Marston (2017) used weed ecology to understand the overall "health" of habitats surrounding the site of Gordion. He argues that examining weed taxa can provide archaeobotanists with valuable information such as whether surrounding grazing lands were overgrazed or representative of healthy grassland communities. Recently, Motuzaite Matuzeviciute et al. (2021) used weed seeds to reconstruct the landscape surrounding the prehistoric site of Chap I in Kyrgyzstan. They observed a high density of *Chenopodium* species, which suggests a nitrogen-rich environment, and Fabaceae species, which could have contributed to nitrogen levels. They also observed several weed species that typically occupy open, moist environments, such as *Carex* species. These data suggested an open, human-constructed landscape that required careful management through irrigation.

Because archaeobotanical studies frequently cover long time periods, they may reveal connections between climate change and changing agricultural practices. A recent study of animal husbandry and plant cultivation in Neolithic and Bronze Age China suggested that increasing environmental exploitation, associated with agricultural diversification and intensification, provided resilience in a period of dramatic climate change (Jing et al. 2020). Another study from Iron Age northeastern Thailand used weed flora to demonstrate a shift from dryland to wetland rice cultivation, likely in response to an increasingly arid climate (Castillo et al. 2018). These examples show that archaeobotanists can use weed ecology knowledge to study human responses to climate change (cropping system adaptation).

We propose that future collaborations between archaeobotanists and weed scientists could also provide insight into weed responses to climate change. Contemporary studies have revealed dramatic impacts of anthropogenic climate change on weed species ranges (Clements and DiTommaso 2011; Peters et al. 2014). Archaeobotanists can examine weed species distributions over the course of the Holocene. By collating all the archaeobotanical research that has taken place within a particular region and time period, researchers can identify sites where a weed species was present or absent. When integrated with paleoclimate data, such

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as rainfall metrics taken from tree rings, this approach might provide information about the bioclimatic niche of the weed species and its potential response to climate change. Caveats to this approach include (1) the possibility that weed species represented at an archaeological site were products of trade rather than components of the plant community surrounding the site, (2) the possibility that non-climate factors (e.g., management practices) excluded weed species from some sites, and (3) the possibility that direct effects of climate change on weeds might be confounded with indirect effects mediated by cropping system adaptation to the novel climate. These caveats might be addressed by combining archaeobotanical data with other data types (e.g., other indicators of provenance) and by adapting the FIBS approach. Some functional attributes could be useful in separating the effects of climate change from the effects of changing management practices on weed communities, but these attributes have not yet been identified.

Conclusion

Archaeobotany is a field that benefits greatly from weed science knowledge. Weed ecological approaches used by archaeobotanists since the mid-20th century have become increasingly sophisticated. These approaches have been used to investigate the provenance of plant remains and numerous aspects of ancient agricultural systems, including crop rotation, sowing time, irrigation, soil fertility, cultivation intensity, and weed management. Archaeobotanical research on these agricultural practices is supported by advances in functional weed ecology. This research might be accelerated by increased collaboration with weed scientists, who can help archaeobotanists identify the best functional indicators of agricultural practices. Increased collaboration may also facilitate progress in weed science. The length of the archaeobotanical record, which in many places stretches back thousands of years, presents a rich data set for weed scientists seeking to understand the long-term effects of human influence on agricultural weed communities. In addition, archaeobotanical data reflect weed species responses to climate. Thus, increased collaboration between archaeobotanists and weed scientists is likely to be beneficial to both fields of study.

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