The anatomy of hügelkultur and dissecting the key claims

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Abstract

Hügelkultur, German for “hill culture”, was first defined in 1962 and adopted by the permaculture community in the subsequent decades. The technique typically involves layering woody organic matter with soil and compost, or other available organic matter, to create a raised bed—which is then planted on all sides. Practitioners claim that the principles upon which hügelkultur function is grounded in science. However, no controlled, replicated research on inherent hügel bed characteristics or performance has been identified in the literature. This review seeks to ground the more prominent claims about hügelkultur by reviewing similar topics in published scientific literature. Hügelkultur proponents claim that, among other things, hügel beds reduce irrigation and fertility requirements, increase soil organic matter content, sequester carbon, and provide a beneficial microclimate for crop production. However, others point out that irrigation and rainfall may lead to runoff and erosion from the relatively steep slopes of the hügel beds; and, as the woody organic skeleton underlying hügelkultur breaks down, settling may harm established plant roots. While some of these claims may have merit based on the current understanding of plant and soil ecology, remain unvalidated in the specific context of hügelkultur. Where commercial applications could apply—e.g. distinct microclimates may have implications for season extension in annual specialty crops—further research is warranted. This review examines common claims found in anecdotal accounts and grey literature against relevant peer-reviewed literature, from related disciplines, to assess their potential validity and propose possible avenues for hügelkultur research.

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Dedication

I dedicate this to my family, who consistently encourage me to follow my dreams. To my parents, who believed in me when I started losing faith in myself, this is for you. To my grandmother, who remains one of my biggest fans, this for you. Oma, you are an inspiration to me, and you provided the light that helped me see the end of the tunnel. My parents and grandmother were my loudest cheerleaders. They helped me regain my momentum and make it to the finish line. This is as much for me as it is for all of you.

Chapter 1 - The Anatomy of Hügelkultur and Dissecting the Key Claims

Abstract

Hügelkultur, German for “hill culture”, was first defined in 1962 and adopted by the permaculture community in the subsequent decades. The technique typically involves layering woody organic matter with soil and compost, or other available organic matter, to create a raised bed—which is then planted on all sides. Practitioners claim that the principles upon which hügelkultur function is grounded in science. However, no controlled, replicated research on inherent hügel bed characteristics or performance has been identified in the literature. This review seeks to ground the more prominent claims about hügelkultur by reviewing similar topics in published scientific literature. Hügelkultur proponents claim that, among other things, hügel beds reduce irrigation and fertility requirements, increase soil organic matter content, sequester carbon, and provide a beneficial microclimate for crop production. However, others point out that irrigation and rainfall may lead to runoff and erosion from the relatively steep slopes of the hügel beds; and, as the woody organic skeleton underlying hügelkultur breaks down, settling may harm established plant roots. While some of these claims may have merit based on the current understanding of plant and soil ecology, remain unvalidated in the specific context of hügelkultur. Where commercial applications could apply—e.g. distinct microclimates may have implications for season extension in annual specialty crops—further research is warranted. This review examines common claims found in anecdotal accounts and grey literature against relevant peer-reviewed literature, from related disciplines, to assess their potential validity and propose possible avenues for hügelkultur research.

Introduction

Hügelkultur, German for "hill culture," is a system of raised beds comprising layers of wood, soil, and compost or other types of organic matter to create, often windrowed, mounds. An individual mound or bed may be referred to as a "hügel bed." The history and origins of hügelkultur are not clear, but the first appearance of the term was "in a 1962 German brochure" written by Herman Andrä in which he "describes the diversity of plants found growing in the woody debris pile in the corner of his grandmothers garden" (Chalker-Scott 2017). Chalker-Scott (2017) suggests that Andrä may have been influenced by Rudolf Steiner, since Andrä included a quote from one of Steiner's 1924 lectures on biodynamics in the book Andrä coauthored with Hans Beba. An English translation of Beba and Andrä's book does not exist. Although their work may be the first to use "hügelkultur" in print, it is likely that the technique of growing on buried woody debris and other organic matter significantly predates any usage of the term (Winter 2015).

Hügelkultur found more widespread use after being popularized by Sepp Holzer, an Austrian writer and farmer who uses and advocates for holistic, nature-based food production practices. Holzer references hügelkultur in his book, *Sepp Holzers Permakultur*, first published in German in 2004, with an English translation first published in 2010. Though Holzer (2010) does not specifically use the word "hügelkultur" in the English translation , he briefly describes the benefits, design, and construction of raised beds utilizing buried wood, likely increasing the use of hügelkultur among permaculture practitioners around the world. (Holzer 2010

). A YouTube video highlighting "nearly a kilometer of hügelkultur beds" constructed in Montana, under Holzer's direction, has garnered over a half-million views (Wheaton 2012).

Permaculture, short for “permanent agriculture,” encourages “conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability, and resilience of natural ecosystems” (Mollison 1988). Hügelkultur, as an example of a man-made agricultural system, simulates natural decomposition on forest floors (Mollison 1988). Permaculture practitioners claim that hügelkultur has several benefits including reduced irrigation (Feineigle 2012, Wheaton 2021) and reduced fertilizer needs (Holzer 2010, Wooldridge 2016), among others. However, prior to 2020, no peer-reviewed research reports on hügelkultur appear in agriculture, horticulture, agroecology, or related literature.

In 2020, hügelkultur is referenced as one of several increasingly common sustainable-gardening practices in urban areas that are influenced by permaculture (Granzow and Jones). Another article from 2020 focuses on the social experiences and awareness that comes from observing and interacting with dead and dying trees and their many parts (Shcheglovitova). Shcheglovitova (2020) describes hügelkultur as “a farming technique where wood is buried to nourish plants, retain water, and build soil”. A Baltimore resident, who began practicing hügelkultur before knowing there was a term for it, describes hügelkultur as his primary growing system because it benefits and builds up the soil (Shcheglovitova 2020).

Given the varied and lengthy history of hügelkultur, practitioners across the world construct hügel beds in unique ways, implementing design features to suit their landscape and utilizing locally available organic matter and/or substrate. In fact, a quick search for “hügelkultur” leads to over 350,000 results. The following section provides an overview of hügelkultur design and construction considerations.

Hügelkultur Design and Construction

Although there are many ways to construct a hügel bed, they all follow the general pattern of creating layers of woody or other durable organic material and soil and/or compost until the desired bed height is reached, or materials are exhausted. At their essence, hügel beds are mounded structures comprised of organic, often with large proportions of ligneous material in their cross-section. This offers flexibility and makes adaptations a logical part of the design process. Material selection and design strategies are often determined based on available resources; geographic location, including environmental conditions; land topography; and personal preference. Before initiating the construction process, assess available resources, including wood species, size, quantities available and proximity to the desired site. Determine the availability of other types of organic matter such as: compost, grass clippings, leaf litter, worm castings, straw, spent mushroom substrates, etc.

It is important to consider the project's size, slope of the land, availability of topsoil, and scale of the project. Smaller scale projects are easier to build without mechanized equipment; but the larger the wood and/or size of the bed may require the use of equipment such as tractors, excavators and/or loaders to move the large amount of material required. Oftentimes, beds are arranged in long, straight beds, curved to match the site's contours. However, hügel beds can be arranged in almost any preferred layout. On sloped ground, Sepp Holzer argues hügel beds should not be oriented parallel to the slope, but rather "at an angle to the slope" (Holzer 2010). Beds parallel to the slope could result in disproportionate water retention toward the top of the slope, or worse, excessive rainfall could cause the relatively low-density wood to float up out of the substructure of the hügel, causing, effectively, a dam break with potential for damage below the hügel (Holzer 2010). Once the installation site and the type and size of materials are determined, the initial step in hügel bed construction is laying out the largest diameter wood, or most massive organic material, in the shape of the desired bed. Some practitioners place this first layer directly on the native soil, with or without tilling. However, if topsoil is a limited resource, digging a trench can provide topsoil for covering the layers in the hügel bed (Fig. 1). This will ultimately reduce the finished height of the bed. Whether using a trench or starting on the soil surface, keep in mind that the final bed will be wider and longer than the bottom layer of wood based on the thickness of soil and organic matter that cover the completed bed. Conducting a complete assessment of materials, goals, and site before starting the construction process is critical to success.

With the base layer of wood in place (Fig. 2), the next step is to start incorporating compost, or fine organic materials, into the bed. It is a good practice to fill and compact these materials between and around the logs to minimize voids in the hügel bed. To complete the base layer, a layer of topsoil is spread evenly over the bed, raked, and compacted. Compaction can be accomplished lightly tamping or by walking on the bed while hand raking the organic material and soil. If freshly cut woody material is used, it is helpful to remove buds from the wood to prevent sprouts from disrupting the bed. Utilizing materials which have been harvested with enough time for the vegetation to completely die can also be useful to prevent this problem.

Subsequent layers are applied to the bed using this same process as the base layer, but with each layer using progressively smaller diameter wood, or other durable organic matter (Fig.3, Fig. 4). Each layer of the bed should be narrower than previous layers to create the sloped sides of the finished hügel bed. Beds may be built with wood as large as 30-45 cm in diameter for the base layer, while wood in the topmost layer may be twigs or small branches with maximum diameters less than 5 cm (Fig. 5). The actual size of materials used across all layers will vary based on availability and capacity to move and position the wood.

Once the final layer of wood is placed, a “cap” of organic matter and soil should be smoothed and fully compacted on all surfaces of the hügel bed (Fig. 6, Fig. 7). Examine the beds to make sure no wood, or large pieces of organic matter are exposed, adding soil and compacting as necessary. Ideally, there should be a minimum of 15 cm of soil on all outer surfaces of the hügel mound to accommodate plants. Assess the slope of the beds, as some practitioners, including Sepp Holzer (2010) argue that a slope of 45 degrees or steeper is desired so that the beds don’t become anaerobic, inhibiting decomposition and plant growth. Add soil and compact as necessary to improve the angle of the slope.

While sometimes disputed, it is a common recommendation to plant the beds immediately. Early crop establishment will help stabilize the soil and may mitigate competition from weeds that could grow if the beds rest before planting (Holzer 2010). Allowing the bed to settle prior to planting may prevent root disruption of young seedlings as inevitable settling will occur (Berger 2013).

Irrigating hügel beds is often critical just after planting and during the early stages of decomposition, the length of which will vary depending on the size and density of the organic material used. In hotter and more arid climates, thorough watering will be essential to provide conditions suitable for germination and root development. South-facing slopes (in the Northern Hemisphere) on beds oriented east-to-west, and west-facing slopes on beds oriented north-to-south may require more frequent irrigation than opposing slopes that tend to have cooler soils and slower evaporation. Such aspect differences are expected to be less drastic on beds with lengthwise north-to-south orientation.

Irrigation techniques may vary based on crop needs, environmental conditions, and available resources. Drip irrigation may be best suited for hügel bed production by minimizing the risks of erosion due to its slower application of water allowing more time for the water to soak into the soil and directly targeting the plants' root zone. However, strategies, such as landscape staples, need to be considered to hold drip tape stationary. Overhead irrigation may work for less steep slopes or where canopies are developed enough to prevent erosion.

Purported Benefits of Hügelkultur

Permaculture practitioners promote hügelkultur based on several perceived benefits, claiming it is a sustainable, even regenerative, system due to the long-term ecosystem services they believe it provides. According to the United States Department of Agriculture, National Institute of Food and Agriculture (2024) to be sustainable, an agricultural system should maximize environmental stewardship and conservation practices, while maintaining or improving production and revenue. Regenerative agriculture takes it a step further, incorporating practices that aim to regenerate (i.e. build/restore) the natural resources an agricultural system relies on. Though no consensus definition of regenerative agriculture has been settled on, most agree that restoring soil health and rebuilding biodiversity are key (Giller et al. 2021). Commonly reported benefits of hügelkultur include reduced water conservation, reduced fertilizer, increased soil organic matter, carbon sequestration, and microclimate modification. A review of these benefits is presented alongside potentially relevant peer-reviewed research.

Increased Soil Organic Matter

Permaculturists claim that the decomposition of wood, and other organic substrates that comprise a hügel bed, such as compost, yard litter, etc., increase soil organic matter, specifically mentioning "humus" (Eliades 2020, Slater 2016a). One blog post defines hügelkultur as "a composting method that uses large pieces of rotting wood as the centerpiece for long term humus building," adding that "plants take advantage of nutrients released during decomposition" (Feineigle 2012). However, this use of the term, "humus", is likely referring to soil organic matter generally—ambiguity surrounding the term persists to this day, especially among hobbyists who use it to describe soil rich in organic matter. The term humus has been used since the Roman era, when it primarily described "soil as a whole" (Waksman 1938). In 1761, humus was first associated with decomposed organic matter, though initial theories about its chemical structure and function led to inconsistent interpretations as the field of organic chemistry emerged (Waksman 1938). Humus refers to various organic compounds that influence soil structure by contributing to aggregate formation and stability (Tiwari et al. 2023). However, humic material can only be extracted in a laboratory setting and the classification of its components does not provide any practical information to apply to soil management strategies (Wander 2004).

Certain constituents recommended for hügel bed construction will contribute to different soil organic matter fractions as they decompose. For instance, the compost and leaf litter will contribute to the labile, or active, soil organic matter fraction (Wander 2004). Small diameter twigs and branches contribute to the slow, or intermediate fraction (Wander 2004). While larger, lignin-rich wood, contributes to the recalcitrant fraction, otherwise known as "passive, stable, and inert [soil organic matter]" (Wander 2004).

The labile fraction, or active pool, is often "equated with biological activity," such as microbial processes that mineralize nutrients (Wander 2004). Other materials in the labile fraction may already be soluble and influence "[soil] chemical reactivity, including exchange and sorption-desorption properties" (Wander 2004). This active pool of organic matter can persist for a few days to a few years, essentially influencing soil nutrient availability and storage in the short-term (Wander 2004). The slow pool, or intermediate, fraction tends to influence soil physical properties, and persists in the soil anywhere from a few years to a few decades (Wander 2004). Recalcitrant pools of soil organic matter "have greater relevance for long-term carbon sequestration, sorption, CEC, and soil water-holding capacity" (Wander 2004).

Water Conservation

Hügelkultur is purported to conserve water by reducing irrigation requirements, especially in well-established beds that are in advanced stages of decomposition. Feineigle (2012) claims that wood, in the late stages of decomposition "…serves an almost identical function as a sponge buried in the ground," storing water that can hydrate plants during dry conditions. Wheaton (2012, 2021) claims that the water holding capacity of a hügel bed is influenced by many factors, including the size, age, and source of organic material used in bed construction. Bigger beds and older beds, or beds with more highly decomposed wood, will reduce irrigation needs more than smaller, younger beds or beds with fresher wood (Wheaton 2021).

Even though the rate and effects of decomposition vary by tree species, water storage capacity increases as decomposing wood becomes more hydrophilic, through increased porosity, wettability, and water retention (Błońska et al. 2018). Błońska et al. (2018) found that the most decomposed wood [in the fifth, and final, decay class] "contained the largest amount of water (69.5%-82.3%)," compared with the third and fourth decay classes with water contents of 31.5 - 56.9 % and 32 - 75.4 %, respectively. Harmon et al. (1986) reported that "[v]ascular plants may send their roots into rotting wood and bark to extract water," while other vascular plants may "root in the mat of decaying fine litter that often accumulates on the surface of coarse woody debris" (CWD), referring to wood on the soil surface. It is reasonable to suggest that since plants mine water from rotting wood on the soil surface, they could likely extract water from decomposing wood beneath the soil surface. These studies support the claim that well-established hügel beds may require less irrigation due to decomposing wood acting as a reservoir in the soil matrix, especially in the late stages of decomposition.

Reduced fertilizer use

Permaculturists also claim that hügel beds require less fertilizer since the decaying wood provides a "consistent source of long-term nutrients" (Feineigle 2012, Holzer 2010, Mollison 1988, Wheaton 2012, Wheaton 2021, Wooldridge 2016). Holzer (2010) states that raised beds, comprised of "bulky material such as whole tree trunks," will provide less nutrients upfront, but as a bed ages, "the supply of nutrients will be steady for many years." Deadwood serves as a reservoir for macronutrients that will eventually make their way into the soil profile (Lasota et al. 2018, Piaszczyk et al. 2020). Although fresh wood, located on the soil surface, contains low amounts of plant-available nutrients, as the complex molecules of intact wood deteriorate, previously unavailable nutrients are made available through processes that include leaching and fragmentation (Harmon et al. 1986). Some forms of nitrogen are released from deadwood through fragmentation in late decomposition, while nitrate-nitrogen and potassium tend to leach from wood during earlier stages of decay (Harmon et al. 1986, Lasota et al. 2018). Fragmentation of logs can require "25 years or more," on the forest floor, and the rate of decomposition is influenced by temperature, moisture, carbon dioxide, oxygen, and the type of wood (Harmon et al. 1986). Laiho & Prescott (2004) added that "[c]oncentrations of N and P usually increase during decay [of CWD on the forest floor]." In general, CWD on the forest floor, contains the largest stores of ammonium-N and Ca in late decomposition, while K content “peak[s] earlier in the decay sequence (Class III or IV [of V])” (Harmon et al. 1986, Lasota et al. 2018).

The same physical changes during wood decomposition that impact water retention also influence the quantity of ions leached from wood (Błońska et al. 2018, Lasota et al. 2018). As the porosity of wood increases, “water penetration to wood and leaching of ions” into the soil increases (Lasota et al. 2018). Lasota et al. (2018) found that different species of wood leach differing concentrations of nitrate-N at certain decay classes. Generally, the final decay class (V) sees the greatest rate of nutrient leaching into soil and deciduous trees tend to leach greater concentrations of ions than coniferous trees (Lasota et al. 2018).

While the addition of large amounts of woody, organic material typically immobilizes soil nutrients during the initial stages of decomposition, especially nitrogen which soil microbes utilize to breakdown the woody material, the low “surface area/volume ratio” of CWD limits nutrient immobilization relative to finer debris, like leaves and sawdust (Laiho and Prescott 2004). Despite the immobilization potential, fine woody debris contributes more N than CWD per unit mass; but, in areas where CWD is prevalent, its contribution of N should not be overlooked

Carbon Sequestration

Carbon sequestration occurs when CO_2, is captured from the atmosphere and stored in ways that prevent, or reduce, the rate at which it is released back into the atmosphere (Zeng 2008). Hügelkultur is reported to sequester carbon as wood is encapsulated in soil while also reducing CO_2 emissions (by not burning wood) (Gedon 2016, Wheaton 2021, Wooldridge 2016). When wood and other vegetation decompose, carbon is returned to the atmosphere through heterotrophic respiration (Zeng 2008). Under anaerobic conditions, the decomposition rate of buried wood decreases, thus reducing the rate at which carbon is returned to the atmosphere and enhancing the longevity of carbon sinks (Zeng 2008). Although Holzer (2010) cautions that hügel beds built with a shallow slope increases the chance of anaerobic conditions due to compaction. Most practitioners claim that beds, even those established in clay soils, are unlikely to be anaerobic due to their porous nature (Alladin 2020). While it is unclear if woody material buried in a hügel bed decomposes under aerobic or anaerobic conditions, it is reasonable to expect the release of carbon from that wood into the atmosphere to be delayed over a period of decades relative to wood decomposing on the soil surface.

In forests, buried wood—downed deadwood buried more than 50% by soil, litter, or ground vegetation—is often overlooked in carbon modeling, and can contribute to the massive carbon pools that are reported in forest ecosystems (Moroni et al. 2015) . In natural forest ecosystems, the amount of buried wood can vary greatly depending on the type of forest. Coniferous forests, highly diverse forests, and forests with shrubs and herbaceous ground covers tend to have more buried wood than other forest types (Moroni et al. 2015) . “[Buried wood] occurred in low quantities in hardwood forests and in large quantities in coniferous forests, where volumes of [buried wood] were occasionally larger than the volume of all other woods, live and dead” (Moroni et al. 2015) . Additionally, younger trees are more productive and utilize more CO_2 than older trees (Zeng 2008); therefore, selectively thinning older trees, especially those with low timber value or from forests or managed landscapes where deadwood is not readily buried by natural processes, for use in a hügelkultur system could increase the carbon sequestration potential of hügelkultur.

Microclimate Modification

Hügel beds are purported to create useful microclimates, which are distinct from the ambient environmental conditions due to shading or other effects. This may extend the growing season and/or support a broader selection of plant species (Koch 2016) . Several factors are purported to contribute to hügel bed microclimates including bed orientation (Fraser 2018, Strauss 2016), bed height (Wandling 2020), and location of plants on hügel slope (e.g., top vs. bottom) (Williams 2015). South- and west-facing aspects are claimed to warm the soil by increasing afternoon, and overall solar exposure, while north- and east- facing aspects receive less direct sun, especially during the heat of the day (Fraser 2018, Strauss 2016, Williams 2015). One source claims that "as wood composts, it warms up the surrounding earth" which "prolongs the growing seasons and shelters frost-sensitive plants" (Oommen 2016).

Although not specific to cultivated systems, a few reports compare the effects of sloped aspects on chemical, physical, biochemical, and biophysical properties of soils in natural landscapes (Begum et al. 2010, Huang et al. 2015, Rezaei and Gilkes 2005). Begum et al. (2010) compared north- and south-facing aspects in a rural region of the Himalayas in Nepal and found that soils on north-facing slopes retained significantly more water than south-facing slopes. In contrast, Rezaei and Gilkes (2005) found that aspect had no influence on soil water holding capacity in semi-arid regions of Iran. However, in those same soils, north-facing slopes, had "lower soil temperatures and less moisture evaporation," which resulted "in less organic matter decomposition and consequently more organic carbon and total nitrogen accumulation in the soil" (Rezaei and Gilkes 2005). Similarly, in the Chinese Loess region, both the "organic C and total N contents [of soils] on the shady and half-shady aspects were significantly higher than" sunny and hilltop aspects (Huang et al. 2015) . In general, shaded north-facing aspects, in the

Northern Hemisphere, tend to have greater soil carbon and nitrogen levels than south-facing slopes, which is associated with greater plant diversity and biomass on north-facing slopes (Begum et al. 2010, Rezaei and Gilkes 2005).

Burnett et al. (2008) found that north- and south-facing aspects affected sub-surface soil temperatures more than air temperatures, with the greatest differences in soil temperatures occurring in winter months, when south-facing aspects reached “as much as 8 °C higher” than north-facing slopes. Differences in sub-surface soil temperature between the aspects were smaller in late-spring and summer months, though the south-facing aspect remained consistently warmer by about 4°C (Burnett et al. 2008).

There is limited research available evaluating how the microclimates created by shady and sunny aspects compare with flat ground, and what potential impact such microclimates have in an agricultural context. Xu et al. (2019) evaluated the differences in soybean (*Glycine max* (L.) Merr) production and biomass accumulation in China on an eastward facing slope with “three transects (West, Center and East) covering sunny slopes, slope shoulders, slope tops, shady slopes, slope bottoms, etc.” Although the study focused primarily on plant growth and included other topographical variables (e.g. concavity), they found a “declining trend [in soybean plant biomass] from the sunny, top, and shady slopes to the bottom of the slope in June” (Xu et al. 2019). The difference in biomass “between the shady and sunny slopes gradually decreased in July, and by August, biomass at the bottom was greater than that on shady slopes and biomass on sunny slopes was at a minimum” (Xu et al. 2019). This finding compliments the findings of Burnett et al. (2008) in that differences between north- and south-facing aspects decrease in summer months.

The microclimatic variations reported on different aspects and the influence on vegetation and plant biomass support the claims that shady and sunny aspects can create distinct microclimates, especially influencing soil temperature, moisture content, and nutrient cycling, which impact plant growth and diversity. As such, hügelkultur may have potential to extend growing seasons—depending on crop selection and regional climate and geography. On sun-warmed south- and west-facing slopes, warmer temperatures may allow for extended plant growth in late fall and early spring months relative to growing in flat beds. On shadier, north- and east-facing slopes, cool-season crops planted in the spring may produce later into hot summer months; and, fall crops may be planted earlier than on traditional flat beds. However, given the small scale of hügel beds compared to natural landforms, it is possible that the differences between opposing aspects might be less pronounced; and, differences in summer, when sun angles are highest, or nearer the equator, may also be limited.

Claims that wood decomposing within the soil profile can produce enough heat to impact plant growth are not likely to be substantiated. This claim rests on a comparison of hügel beds to compost piles. While, thermogenesis, heat generated from aerobic decomposition of organic matter (as in compost) is a well-known phenomenon in composting, no published research has been identified that supports the contention that buried wood, especially as whole logs and branches, behave in a manner similar to compost—generating appreciable heat capable of warming surrounding soil. Compost piles with high C:N ratios take longer to enter the high-temperature phase of composting, but the duration of this thermophilic phase increases with higher C:N ratio (Yang et al. 2021). Wood chips from hardwoods and softwoods have average C:N ratios above 500 and 600, respectively (Rynk et al 1992). However, no study has been identified that measures temperature with compost C:N ratio starting above 54, an order of magnitude lower than wood chips. In addition to the C:N ratio, aeration, particle size, pile size, moisture content and pH must all be within their optimal ranges to induce significant heating of compost (Parr et al. 1994). Aeration of compost is the primary factor affecting the rate of decomposition, and therefore heating, in compost (Guo et al. 2012)—a feature not shared with hügelkultur. While it is unlikely that hügelkultur will produce noticeable heat in most cases, future research could investigate aerating hügel beds or manipulating feedstock size and/or C:N ratios to produce thermogenic bed heating.

Potential Limitations of Hügelkultur

Most hügelkultur resources emphasize the potential benefits, while far fewer detail the possible limitations of this system. One potential limitation of hügel beds is "excessive use of rich organic material" (Chalker-Scott 2017). Chalker-Scott (2017) references the eponymous 1962 German brochure which instructs would-be adopters to "include the addition of a foot of dead leaves, a few inches of composted manure, and three to four inches of compost." Chalker-Scott (2017) claims that large amounts of organic matter could lead to nutrient leaching and ultimately "contaminat[e] soil and water habitats"—citing a Cornell Extension factsheet on compost pad construction (Harrison et al. 2005)—but fails to acknowledge that, unlike compost windrows, hügel beds are generally planted at all times (Holzer 2004), reducing the velocity of water impacting the surface and thus the runoff potential, and providing a potential sink (growing plant material) for excess nutrients, minimizing leaching (Reeves 1994). Regardless of whether the 1962 publication suggested excessive organic matter feedstocks, those quantities of organic matter are not recommended in more-recent and widely available hügelkultur construction guides (Eliades 2020, Feineigle 2012, Wheaton 2021). While many sources say hügel beds could include compost, manure, leafy debris, etc. in addition to wood, there are no specifications listing minimum requirements, and most recommend at least an outer layer of soil to enclose organic matter layers (Eliades 2020, Feineigle 2012, Wheaton 2021). Additionally, adding substantial amounts of woody material may immobilize some fraction of the mineralized nutrients, subject to runoff and leaching, especially nitrogen, though this effect would be limited by the stage of decomposition and the size and "surface area/volume ratio" of the wood (Laiho and Prescott 2004). While nutrient leaching is an important consideration, and research specific to the hügelkultur context would be informative, it is likely that today's hügel beds are constructed with less extreme quantities of unprotected, nutrient-rich organic matter, and thus less prone to leaching and runoff.

Chalker-Scott (2017) also highlights the potential for weeds to become unmanageable without incorporating mulch. In contrast, several permaculture sources suggest the opposite, including Bogdanowicz (2021), who claims hügel systems are "weed-free." It is unlikely that hügel beds are inherently weed-free systems, yet experienced permaculturists indicate that hügel beds are easier to weed (Dalziel 2014) or require much less weeding than traditional gardening systems (Blegen 2015, Ward 2019). Further, many permaculturists recommend covering hügels with a mulch layer and/or planting as soon as possible to cover the soil and reduce potential weed pressure (Blegen 2015, Holzer 2010

). While Chalker-Scott's (2017) suggestion of incorporating mulch is true of any agricultural system, including hügel beds, research to identify significant differences between weed pressure in traditional flat beds and hügelkultur is needed to support or refute claims about excessive weed pressure.

At least one hügelkultur critic has suggested that Beba and Andrä's initial suggestion to "[plant] fruit trees and bushes in them" would be detrimental as the beds "collapse over time, requiring rebuilding" (Chalker-Scott 2017). Yet, whether planting trees on hügel beds is a good idea remains contested in the hügelkultur community. Some permaculturists advise against placing trees on a hügel bed specifically citing settlement and potential air pockets as detrimental to tree success (Gjesdal 2019), while others suggest hügel beds may not provide sufficient stability for fruit trees, other than, perhaps, temporary nursery stock (Slater 2016c). Settling of hügel beds is widely acknowledged by permaculture practitioners (Dalziel 2014, Holzer 2010, Slater 2016b, Wandling 2020, Williams 2015, Winter 2015, Woolridge 2016); however, no anecdotal or research reports have been identified that indicate that subsidence of hügel beds occurs fast enough or is substantial enough to significantly impact plant survival. Future research evaluating settlement rates (controlling for variables like: construction method; wood species composition, age, and size; size and extent of air gaps; and C:N ratio of hügel constituents) could help future adoptees better design and plan hügel beds for optimal management and crop selection. Even with such research, environmental and climatic factors such as rainfall, temperature, soil moisture, composition, and texture, etc. will likely impact the rate of decomposition and bed settlement. Recognizing that settlement is a concern, some permaculturists suggest "adding a fresh layer of chop and drop green manure or compost to the surface each year" (Feineigle 2012). "Chop and drop" is a permaculture term referring to pruned and collected branches, leaves, or entire plants are left on the soil surface acting as a mulch layer and ground cover; in hügelkultur, this would add fresh organic matter back to the bed (Long 2017). Regardless, settlement should be expected as an inherent condition of hügel bed decomposition.

The construction process may be another limitation of hügelkultur, depending on the size of the desired bed(s). Large-scale beds, that incorporate large tree trunks and/or long trenches, may require access to equipment, such as a loader, excavator, or tractor, in addition to large quantities of woody material, substantial physical labor, and time. A cost-benefit analysis during planning may help a grower establish whether a hügel bed is feasible or to determine an appropriate scale of hügel bed[s] based upon available resources. Smaller mounds for home growers or small-scale growers, wanting to incorporate them as a part of a larger system could be more feasible as the amount of equipment and time needed is lower.

Conclusion

As with any agricultural system, there are likely to be benefits and limitations. In the case of hügelkultur, several purported benefits may offset potential disadvantages, at least in some circumstances, but no replicated, controlled research has been identified within the context of hügelkultur, specifically. Substantial opportunity exists for research to advance knowledge about hügelkultur and better understand hügelkultur as a production system.

Short-term research should verify the presence and extent of microclimates and how bed orientation and height, time of year, and local climatic conditions may influence those microclimates. Further, researchers should evaluate how those microclimates could be leveraged in specialty crop production vis-à-vis season extension, crop selection, etc. Incorporating soil, canopy, and air temperature data along with PAR data may help understand the extent of microclimatic differences, their influence on crop production, and how they evolve over time. Additionally, research should investigate soil nutrient availability during the establishment phase (i.e. the first one to two years). Because hügelkultur construction involves loading the soil profile with substantial amounts of both labile and recalcitrant organic matter, it is important to understand the implications for crop production in those early years.

Since nutrient availability and water holding capacity of decomposing wood increases in advanced stages of decomposition ((Błońska et al. 2018, Harmon et al. 1986, Lasota et al. 2018), future long-term research could explore the evolution of nutrient availability and soil moisture throughout the life of a hügel bed. Similarly, we recommend experiments evaluating soil structure and the influence of humic substances in hügelkultur over time. If the purported benefits of hügelkultur are substantiated, then future research should help identify hügelkultur best practices, such as how the wood species, size, and freshness affect the functions of hügel beds; and, how to manage erosion, weed growth, and settling, among other maintenance considerations. Hügelkultur may also provide a lens into the broader research on carbon sequestration.

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Figures

Figure 1. The hügel bed construction process may start by digging an optional trench to ensure enough soil is available to complete all the layers of the bed and cover the completed hügel mound. A mini excavator is used to dig the trenches for the research plots at Kansas State University's Willow Lake Student Farm**.**

Figure 2. During the hügel bed construction, the largest wood (by diameter) is placed in the trench to create the base layer of the hügel bed. The research plots at Kansas State University's Willow Lake Student Farm utilized primarily *Populus deltoides*.

Figure 3. During the hügel bed construction process, the second layer of the hügel bed starts by adding slightly smaller wood on top of the tamped and raked soil and compost mixture of the first layer at Kansas State University's Willow Lake Student Farm.

Figure 4. A hügel bed that is partially covered with soil and compost as the third layer of the bed is established at Kansas State University's Willow Lake Student Farm.

Figure 5. The final layer of the hügel bed with small twigs and branches before being topped with soil and compost at Kansas State University's Willow Lake Student Farm.

Figure 6. A nearly finished hügel bed, just before making the final touches of raking the slopes and covering all exposed wood at Kansas State University's Willow Lake Student Farm.

Figure 7. The completed hügel beds at the Kansas State University Willow Lake Student Farm research plot are covered with soil and compost that has been tamped and raked to created even slopes without any exposed wood**.**